SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

# Assessment of a RES-based $H_2$ production-storage system towards a zero-emission cycling based transportation

PhD dissertation

Dimitrios Apostolou

Aarhus BSS
Aarhus University
Department of Business Development and Technology (BTECH)
2020

# ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor Associate Professor Dr. George Xydis for the guidance, support, and motivation he selflessly offered during the realisation of this PhD research. His guidance helped me to improve as a researcher and as a person.

I would also like to express my sincere thanks to the ‘Centre of Energy Technologies’ research group members of Aarhus University and especially Associate Professor Dr. Peter Enevoldsen for his guidance, support and collaboration throughout the entire PhD project.

My sincere thanks also go to the team of ‘Aragon Hydrogen Foundation’ research centre and especially my co-supervisor Dr. Vanesa Gil, Mr. Pedro Casero, and Mr. Nicolás Van Dijk for their precious support and guidance throughout the experimental phase of this research.

I would also like to thank the researchers and personnel of ‘INRASTES Demokritos’ research centre for hosting and helping with my research on different hydrogen storage topologies.

My gratitude also goes to the entire Academic and administrative personnel, and students of the ‘Department of Business Development and Technology’ of Aarhus University for their collaboration, support and fruitful discussions.

Last but not least, my sincere gratitude goes to my family who believed in me during this journey.

*To Kalypso and Jason for having patience with me and providing endless support and encouragement*

# EXECUTIVE SUMMARY

During the last two decades, the research on energy storage systems able to facilitate the penetration of renewable energy sources in the electricity grids has enhanced the development of novel technologies to mitigate the environmental impacts from the use of fossil fuels. The achieved reduction of energy industry-induced greenhouse gas emissions in many countries via the implementation of renewable technologies indicated the path to be followed in other carbon-intensive sectors contributing significantly to environmental pollution. One of the sectors still presenting a continuous increasing trend in the emission indicators comprises the transportation. As documented in many reports and scientific articles, urban road transportation contributes to more than 40% of the total transport-induced emissions suggesting that there is a large potential to reduce the urban pollution by adopting 'green' vehicle technologies and their respective refuelling/recharging infrastructure.

The scope of this PhD project was to assess the implementation of hydrogen production technologies in the light-duty urban mobility infrastructure through the investigation of the relevant socio- and techno-economic relevant aspects to the transition to carbon-free mobility. To this end, eight articles were presented aiming to address the problem of interest as described by the following research questions:

1. *What are the socio-economic prospects of the light-duty FCEVs' private transportation and its respective infrastructure?*

2. *Why and how a 'green' hydrogen production system participating in wind power and electricity markets could be a viable solution towards sustainable light-duty hydrogen transportation?*

3. *Which type of hydrogen refuelling infrastructure for cycling-based transportation is the most economically feasible solution from an investor and customer perspective?*

Two scientific articles were submitted and published in the context of the first research question focussing on the one hand on the techno-economic prospects of hydrogen transportation as documented in the international literature, and on the other on the socio-economic perspective of the Danish public concerning the adoption of hydrogen technologies in private transportation. The first article consisted of a literature review to identify the status of hydrogen technologies including vehicles and the respective refuelling infrastructure, in terms of number of entities and associated costs. Analyses of the future trends of how entity numbers and capital cost of refuelling infrastructure, and refuelling cost will evolve revealed different scenarios including pessimistic and optimistic cases. The refuelling stations' capital cost is expected to increase in the short term but subsequently decrease to lower than current cost, while the renewable hydrogen refuelling cost is expected to decrease and stabilise by 2040 below 6 €/kg$H_2$ on average. The second paper consisted of a survey applied to a sample of the Danish population aiming to identify the socio-economic prospects of hydrogen private mobility in Denmark. The questionnaire the respondents were asked to answer, was developed accordingly to assess the stated hypotheses describing the socio-techno-economic aspects of the transition to hydrogen mobility. The results indicated that lack of technology knowledge, high vehicle capital cost, absent media support, and inadequate infrastructure are the most important factors hindering the expansion of the hydrogen mobility market.

The second research question was investigated through two published scientific articles including a literature review on the state-of-art of hybrid wind and hydrogen configurations, and a research paper comprising a modelling and simulation of a hydrogen system participating in the electricity and transportation markets. The first article documented the benefits and drawbacks of wind-hydrogen topologies either connected to the electricity grid, operating as autonomous systems, or providing fuel for transport applications. The results showed that the round-trip energy efficiency of such systems is dependent on the under-investigation topology, while the hydrogen fuel cost is dynamically affected by the production method and refuelling process applied. The second article presented an optimisation method to find the most financially viable solution of a hydrogen system participating in the electricity, the transportation or both markets. The methodology focussed on assessing the economics of such a system from the investor's perspective by identifying the scenario and the respective hydrogen fuel cost in the context of participating in the transportation market, which would provide a feasible business case. The results showed that in the Danish energy market, the most realistic scenario comprises of a 'green' hydrogen system participating in the electricity market as a consumer (i.e. load demand/response role) and in the transportation market as a fuel provider to end-user industries with an average hydrogen production cost of 4.1 €/kg$H_2$.

To address the third research question, four research articles were published/submitted including the investigation of different hydrogen refuelling process options delivered by the respective station topologies. The first article examined a case study of sizing and optimising the operation of an autonomous hydrogen refuelling station to produce electrolytic hydrogen from wind power. The sizing algorithm of all components was based on the assumed hydrogen demand of a small Danish city and the respective available wind resource. The hydrogen demand was assumed to be used for cycling mobility through the adoption of fuel cell bicycles. The results showed a high hydrogen cost, exceeding 50 €/kg$H_2$, due to the estimated low demand, limited wind resource, and high capital and operating costs of the station. However, the actual cost that the consumer is called to pay during a refuelling process is less than one Euro per refuelling process as the hydrogen storage of this type of vehicles is in the order of grams. The applied sizing and optimisation algorithm resulted to a proper sizing of the system as approximately 90% of the annual demand could be covered without implementing a system that would present a non-affordable refuelling cost for the consumer.

By taking into account the results of the previous article, the second paper experimentally examined the operation and hydrogen consumption of a fuel cell bicycle. Low-pressure refuelling options of the vehicle were theoretically computed, the responses of a survey shared to the experiment's participants concerning hydrogen-cycling mobility were documented and analysed, and the final economic results were compared to urban vehicle counterparts. The results showed that the most feasible refuelling business option also accepted by the participants comprised the grid-connected on-site refuelling station with a low-end hydrogen cost at 22 €/kg$H_2$. Following the results of the second article, the third published paper experimentally investigated the refuelling costs of a high-pressure grid-connected on-site refuelling station and compared it with the low-pressure alternative. Subsequently the results were disseminated to a workshop's participants to get an overview about what would be, from an economic point of view, their opinion concerning the refuelling processes. The analysed results indicated that although the refuelling cost per kg$H_2$ increases at higher dispensing pressures, the cost ratio per travelled km remains almost constant at 0.019 €/km. Despite this, the workshop's participants stated that what matters to them was the final cost they need to pay for a refuelling process in conjunction with the autonomy of the vehicle and their commuting habits. To this end, the most appealing option to them was the low-pressure refuelling process, which would secure the lowest price without compromising their commuting needs.

The fourth and final article presented in this thesis to find the most financially feasible solution for both investors and consumers in the context of 'green' hydrogen light urban mobility, consisted of a comparative analysis between a grid-connected on-site and an offsite hydrogen refuelling station. The investigated scenarios included hydrogen refuelling stations able to dispense hydrogen fuel to either low-pressure compressed or metal hydride vehicle on-board tanks. The above-mentioned scenarios were applied in two European Union countries with different economic indicators to assess how external parameters could affect the hydrogen fuel cost.

The results indicated that the lowest investment cost with the lowest hydrogen fuel price but with higher refuelling times could be achieved in the offsite metal hydride configuration. However, due to the intrinsic characteristic of metal hydride storage materials consisting of the inability to reversibly release all the absorbed hydrogen quantity, the initial quantity of stored hydrogen needs to be higher than the demand. This results to a higher cost for the consumer that is at least similar or even higher than the compressed refuelling option. It was also computed that the hydrogen fuel cost is highly dependent on external factors including the labour and operating and maintenance costs, and taxation. All these factors differ significantly between countries and thus it can be said that the best refuelling option for this type of transportation in one country might not be valid for another.

In conclusion, this PhD project provides a guideline to transportation stakeholders towards a transition from a fossil fuel- to a renewable-based transport sector via the implementation of hydrogen urban mobility. The methodology described in the quoted papers can be used to develop a viable and adequate hydrogen refuelling market. The decision about which type of refuelling infrastructure is the best from a socio-techno-economic perspective needs an in-depth and multi-dimensional investigation. For Denmark where the electricity mix is significantly based on renewable energy sources, an offsite compressed gas delivery-to-vehicles hydrogen refuelling station supplied from a centralised 'green' hydrogen production facility is the most renewable-based feasible solution for both investors and consumers. In contrast, countries where the electricity mix is based on conventional power generating units, an autonomous compressed-to-vehicles on-site hydrogen refuelling station might be the next environmentally accepted alternative.

# DANISH EXECUTIVE SUMMARY

I de seneste to årtier har forskning i energisystemer, der kan understøtte integreringen af vedvarende energikilder i elnettet, udviklet nye teknologier til at reducere miljøbelastningen fra anvendelsen af fossile brændstoffer. Mange lande har nedbragt deres udledning af drivhusgasser i industrien ved øget brug af vedvarende energi. Dette vil også kunne implementeres i andre sektorer, der udleder store mængder af $CO_2$ og dermed bidrager væsentligt til miljøforurening. En af de sektorer, der udgør en stadig stigende del af udledningen, er transportsektoren. Ifølge flere rapporter og videnskabelige artikler udgør bytransport 40 % af de samlede transportrelaterede emissioner, hvilket peger på, at der er et stort potentiale i at reducere forurening i byer ved at indfase 'grønne' køretøjsteknologier samt udvikle tankningsinfrastrukturen.

Formålet med indeværende ph.d.-afhandling var at vurdere implementeringen af lette brintdrevne køretøjer i byer gennem en undersøgelse af relevante samfundsmæssige, teknologiske og økonomiske aspekter, der fremmer en kulstoffri mobilitet. I den forbindelse blev der udarbejdet otte artikler, der skulle belyse problemstillingen beskrevet med følgende forskningsspørgsmål:

1. *Hvad er de samfundsøkonomiske udsigter for brintbiler samt den dertilhørende infrastruktur?*

2. *Hvorfor og hvordan kan et 'grønt' brintproduktionssystem på vind- og elmarkedet være en fremtidig løsning i omstillingen til bæredygtig brinttransport?*

3. *Hvilken type tankningsinfrastruktur til brintdrevne elcykler er den mest økonomiske set fra et investerings- og kundeperspektiv?*

For at besvare det første forskningsspørgsmål blev der publiceret to videnskabelige artikler, som 1) fokuserede på det teknologiske og økonomiske aspekt ved brinttransport med udgangspunkt i internationale publikationer samt 2) den danske befolknings skepsis over for brintbiler set ud fra et samfundsøkonomisk perspektiv. Den første artikel var en litteraturgennemgang, der havde til formål at give en status på brintteknologier, herunder brintbiler og tankningsinfrastrukturen både i forhold til antal brintstationer samt omkostninger. Analyser af fremtidige scenarier for dette samt prisen på brint viste både positive og negative forhold. På kort sigt forventes udgifterne til brinttankstationer at stige, men efterfølgende at falde til et lavere niveau end det nuværende, mens prisen på brint forventes at falde og ligge stabilt i 2040 (i gennemsnit under 6 €/kg$H_2$). Den anden artikel beskrev resultatet af en spørgeskemaundersøgelse blandt et udsnit af den danske befolkning med det formål at identificere brintbilers samfundsøkonomiske udsigter i Danmark. Spørgeskemaet blev udarbejdet med henblik på at vurdere hypoteserne vedrørende de samfundsmæssige, teknologiske og økonomiske aspekter ved overgangen til brintmobilitet. Resultaterne indikerede, at manglende teknologiforståelse, høje priser på køretøjerne, manglende opbakning fra medierne samt en utilstrækkelig infrastruktur er de vigtigste faktorer, når det kommer til udbredelsen af brintbiler.

Det andet forskningsspørgsmål blev undersøgt gennem to publicerede videnskabelige artikler (herunder en litteraturgennemgang af de nyeste hybride vind- og brintkonfigurationer) samt en forskningsartikel, der omfattede en modellering og simulering af et brintsystem på el- og transportmarkedet. Den første artikel dokumenterede fordelene og ulemperne ved vind-/brinttopologier, der enten er tilsluttet elnettet, fungerer som autonome systemer eller leverer brændstof til transportapplikationer. Resultaterne viste, at retureffektiviteten i sådanne systemer afhænger af topologien, mens brintomkostninger påvirkes dynamisk af den anvendte produktionsmetode og tankningsproces. Den anden artikel præsenterede en optimeringsmetode, der skulle finde frem til den økonomisk mest fordelagtige løsning på et brintsystem på enten el- eller transportmarkedet – eller begge. Ved at identificere scenariet og de respektive brintomkostninger på transportmarkedet blev metoden brugt til at vurdere, om et sådant system ville være en økonomisk gevinst for investorer – og dermed også et forretningspotentiale. Resultaterne viste, at det mest realistiske scenarie på det danske energimarked er et ’grøn’ brintsystem, der er på elmarkedet som forbruger (dvs. med et fleksibelt elforbrug) og på transportmarkedet som brændstofudbyder til industrien med en gennemsnitlig produktionsomkostning på 4.1 €/kg$H_2$.

For at besvare det tredje forskningsspørgsmål blev fire forskningsartikler publiceret, inklusiv en undersøgelse af forskellige tankningsmuligheder på de respektive tankstationer. Den første artikel var en casestudy til dimensionering og optimering af driften på en selvejet brinttanksstation, der producerede elektrolytisk brint fra vindkraft. Størrelsesalgoritmen for alle komponenter var baseret på det forventede brintbehov i en lille dansk by samt den tilsvarende tilgængelige vindkilde. Det var en forudsætning, at brintbehovet blev anvendt til cykelmobilitet i form af brintcykler. Resultaterne viste høje brintpriser (over 50 €/kg$H_2$) som følge af den anslåede lave efterspørgsel, den begrænsede vind samt stationens høje driftsudgifter. Imidlertid er den faktiske pris, som kunden skal betale for tankning, mindre end 1 € pr. tankning, da brintlagringen for denne type køretøj er i størrelsesordenen gram. Den anvendte dimensions- og optimeringsalgoritme gav en korrekt dimensionering af systemet, da ca. 90 % af den årlige efterspørgsel kunne dækkes uden at implementere et system, der ville være for dyrt for forbrugeren.

Med udgangspunkt i den første artikel undersøgte den anden artikel hypotetisk driften og brintforbruget på en brintdrevet elcykel. Mulighederne for at tanke køretøjet under lavt tryk blev teoretisk beregnet, svarene fra undersøgelsens testpersoner vedrørende brintcykelmobilitet blev dokumenteret og analyseret, og de endelige økonomiske resultater blev sammenlignet med bykøretøjer. Resultaterne viste, at den foretrukne tankningsmulighed (også blandt deltagerne) var en nettilsluttet tankstation, hvor brinten laves på stedet til en lav brændselspris på 22 €/kg$H_2$. Den tredje artikel undersøgte hypotetisk omkostningerne ved at tanke på en nettilsluttet tankstation, hvor brinten produceres på stedet og tankes under et højt påfyldningstryk. Resultaterne blev sammenlignet med omkostningerne ved at tanke under et lavt tryk og herefter formidlet til deltagerne på en workshop for at finde frem til deres foretrukne type brintoptankning set ud fra et økonomiske synspunkt. Resultaterne indikerede, at selvom brintomkostningerne pr. kg/$H_2$ stiger ved højere påfyldningstryk, er omkostningerne pr. tilbagelagt kilometer stort set de samme med 0.019 €/km. Til trods for dette gav workshopdeltagerne udtryk for, at de vigtigste faktorer for dem, var de samlede økonomiske omkostninger samt køretøjets køreegenskaber og deltagernes pendlervaner. Derfor foretrak de tankningen med det lave påfyldningstryk, da de her ville skulle betale mindst uden at gå på kompromis med deres pendlerbehov.

For at finde den økonomisk mest fordelagtige løsning for både investorer og kunder, når det kommer til valg af grønne transportmidler, præsenterede den fjerde og sidste artikel i indeværende afhandling en komparativ analyse af en nettilsluttet tankstation, der laver brinten på stedet, og en tankstation, hvor brinten fragtes ud til tankstationen. De undersøgte scenarier omfattede brinttankstationer, der både kan fylde brint på bilens lavtryks- og metalhydridtanke. Scenarierne blev anvendt i to EU-lande med forskellige økonomiske indikatorer med henblik på at vurdere, hvordan eksterne parametre kunne påvirke prisen på brint.

Resultaterne viste, at man med metalhydridmodellen på tankstationer, hvor brinten skal fragtes til, kunne opnå de laveste investeringsomkostninger i forhold til prisen på brint – dog med længere tankningstider. Men fordi metalhydrider ikke er i stand til at frigive den absorberede brintmængde, skal den oprindelig mængde af lagret brint være større end forbruget. Det resulterer i den samme eller endda en højere pris for forbrugeren end ved den komprimerede tankning. Det blev desuden beregnet, at prisen på brint afhænger meget af eksterne faktorer, herunder udgifter til løn, drift, vedligeholdelse og skatter. Disse faktorer varierer fra land til land, og derfor er den bedste tankningsmulighed i et land ikke nødvendigvis den bedste i et andet.

Sammenfattende giver denne ph.d.-afhandling en række input til interessenter inden for transportsektoren i forbindelse med overgangen til grøn mobilitet. Metoden beskrevet i artiklerne kan bruges til at udvikle et bæredygtigt og dækkende marked inden for brintdrevne transportmidler. Der er behov for en dybdegående og flerdimensionel undersøgelse af, hvilken tankningsinfrastruktur der – set ud fra et socialt, teknologisk og økonomisk perspektiv – er den bedste. I Danmark, hvor en stor del af den producerede energi kommer fra bæredygtige energikilder, er tankstationer, hvor brinten fragtes til tankstationen af en 'grøn' producent af vedvarende energi, den mest bæredygtige løsning for både investorer og forbrugere, mens det bedste bæredygtige alternativ i lande, der producerer energi fra konventionelle energikilder, formentligt er selvejede tankstationer, hvor brinten laves på stedet.

# Table of Contents

# List of Figures

# List of Tables

# NOMENCLATURE

### *Greek Letters*

| | |
|---|---|
| $\alpha$ | Activity coefficient |
| $\Delta$ | Technical availability of a wind turbine |
| $\Delta H$ | Enthalpy of formation |
| $\eta_{el}$ | Electrolyser's efficiency |
| $\eta_F$ | Faraday's efficiency |
| $\Phi$ | Tax on income |
| $\omega$ | Mean power coefficient |

### *Abbreviations*

| | |
|---|---|
| *AFV* | Alternative fuel vehicle |
| *BEB* | Battery electric bicycle |
| *BES* | Battery electric scooter |
| *BEV* | Battery electric vehicle |
| *BOP* | Balance of plant |
| *CAES* | Compressed air energy storage |
| *CAPEX* | Capital expenditures |
| *CEMAC* | Clean energy manufacturing centre |
| *CF* | Capacity factor |
| *CFI* | Comparative fit index |
| *DC* | Direct current |
| *EAFO* | European alternative fuels observatory |
| *EES* | Electrical energy storage |
| *Eq* | Equation |
| *EU* | European union |
| *EV* | Electric vehicle |
| *FC* | Fuel cell |
| *FCEB* | Fuel cell electric bicycle |
| *FCEV* | Fuel cell electric vehicle |
| *FCES* | Fuel cell electric scooter |
| *GHG* | Greenhouse gas |
| *HHV* | High heating value |
| *HRS* | Hydrogen refuelling station |
| *ICE* | Internal combustion engine |
| *IEA* | International energy agency |
| *IRR* | Internal rate of return |
| *ISI* | Integrated sustainability index |
| *LC* | Life cycle |
| *LCA* | Life cycle assessment |
| *LCOE* | Levelised cost of energy |
| *MH* | Metal hydride |
| *NG* | Natural gas |
| *NPV* | Net present value |

| | |
|---|---|
| *NREL* | National Renewable Energy Laboratory |
| *O&M* | Operational and maintenance |
| *OECD* | Organisation for Economic Co-Operation and Development |
| *OPEX* | Operating expenditures |
| *PEM* | Proton exchange membrane |
| *PEOU* | Perceived ease of use |
| *PHEV* | Plug-in hybrid electric vehicle |
| *PHS* | Pumped hydro storage |
| *PP* | Payback period |
| *PU* | Perceived usefulness |
| *PV* | Photovoltaic |
| *P2G* | Power to gas |
| *R&D* | Research and development |
| *RES* | Renewable energy sources |
| *RMSEA* | Root mean square error of approximation |
| *RQ* | Research question |
| *SEM* | Structural equation model |
| *SC* | Scenario |
| *SMR* | Steam methane reforming |
| *SOC* | State of charge |
| *TSO* | Transmission system operator |
| *URFC* | Unitised reversible fuel cell |
| *V2G* | Vehicle to grid |
| *V2L* | Vehicle to load |
| *WH* | Wind-hydrogen |
| *WT* | Wind turbine |
| *WtW* | Well to wheel |

## *Symbols*

| | |
|---|---|
| $A$ | Surface area, $m^2$ or $cm^2$ |
| $Ad$ | Depreciation, € |
| $B$ | Bias parameter |
| $c$ | Specific thermal capacity, $J\ (kgK)^{-1}$ |
| $c_w$ | Wind speed scale factor |
| $C$ | Thermal capacity, $J\ {}^{o}C^{-1}$ or $J\ K^{-1}$ |
| $CV_{coef}$ | Conversion factor in present values |
| $D_{dist}$ | Average daily distance travelled, km |
| $E$ | Energy, kWh |
| $Ec$ | Energy consumption ratio, $kWh\ kgH_2^{-1}$ |
| $E_{el}$ | Electricity demand of the electrolyser, kWh |
| $E_{WT}$ | Required production from the wind turbine, kWh |
| $F$ | Faraday’s constant |
| $f$ | Faraday’s parameter |
| $FC_{OM}$ | Operating and maintenance costs, € |
| $FC_{par}$ | Annual O&M parameter of the entire $H_2$ system |
| $f_{cost}$ | Construction work cost parameter |
| $h_{day}$ | Hours of the day |
| $h_{operat.}$ | Operating hours, h |
| $h_{year}$ | Hours of the year |

| | |
|---|---|
| $I$ | Current, A |
| $I_k$ | Binary factor |
| $i$ | Loan rate of interest |
| $i_d$ | Current density, A cm$^{-2}$ |
| $IC$ | Investment cost, € |
| $Iinst$ | Payment amount of the loan, € |
| $Iloan$ | Interest of loan, € |
| $In$ | Insurance cost, € |
| $k$ | Wind speed shape factor |
| $l$ | Membrane thickness, cm |
| $LHV_{H2}$ | Low heating value of hydrogen, kWh g$^{-1}$ |
| $LL$ | Rest of the loan amount, € |
| $m_d$ | Electrolyte conductivity parameter, V |
| $\dot{m}$ | Mass flow rate, kg s$^{-1}$ or g s$^{-1}$ |
| $m_{H2,cons}$ | Hydrogen mass consumed during refuelling, $gH_2$ |
| $m_{H,stored}$ | Hydrogen mass inside bike's tank, $gH_2$ |
| $m_{H2,electr}$ | Daily $H_2$ mass production, $gH_2$ |
| $M$ | Mass, kg |
| $M_{H2}$ | Daily hydrogen production, $gH_2$ or $kgH_2$ |
| $M_{H2bfr}$ | Mass capacity of buffer tank, $gH_2$ or $kgH_2$ |
| $M_{H2dem}$ | Hydrogen daily demand, kg |
| $M_{H2hp}$ | Mass capacity of high-pressure tank, $kgH_2$ |
| $MW$ | Molecular weight, kg mol$^{-1}$ |
| $n_c$ | Number of electrolytic cells |
| $n_d$ | Gas diffusion layer porosity parameter, cm$^2$ A$^{-1}$ |
| $\dot{n}_{H2}$ | Hydrogen production flow rate, mol s$^{-1}$ |
| $N$ | Number of survey elements |
| $N_{bikes}$ | Estimated number of daily refuelling processes |
| $N_{bikes,hose}$ | Daily number of refills per hose |
| $N_{days}$ | Days of the year |
| $N_{FCEB}$ | Calculated number of daily bike refills |
| $N_{HRS,hose}$ | Total number of station's hoses |
| $N_{inh}$ | City's inhabitants |
| $OM$ | O&M costs of different components as percentage of CAPEX |
| $p$ | Pressure, Pa or bar |
| $p_{el}$ | Electrolyser's output pressure, bar |
| $P$ | Power, kW |
| $PO$ | Labour wage, € |
| $Q$ | Heat, W |
| $r$ | Ohmic parameter |
| $r_c$ | Weighted average cost of capital |
| $r_m$ | FC membrane resistance, Ω cm |
| $R$ | Universal gas constant |
| $R_{bike}$ | Average range of fuel cell bike, km |
| $RC$ | Diminishing factors |
| $Rel$ | Electricity price € kWh$^{-1}$ |
| $R_{int}$ | FC internal resistance, Ω cm$^2$ |
| $Rn$ | Annual land lease cost, € |
| $Rt$ | Thermal resistance, K W$^{-1}$ |
| $s$ | Anode's overvoltage parameter |
| $t$ | Cathode's overvoltage parameter |
| $T$ | Temperature, ºC or K |
| $t_{other}$ | Additional time during refill, min |
| $Tr$ | Revenues of $H_2$ sales, € |

| | |
|---|---|
| $t_{refill}$ | Time to refill $H_2$, min |
| $U$ | Voltage, V |
| $V$ | Wind speed, m/s |
| $v$ | Volume, L |
| $v_{bfr,WV}$ | Buffer tank's water volume, L |
| $w$ | Weight factor |
| $X_{H2O}$ | Molar fraction of water |
| $Y$ | Survey's target variable |
| $z$ | Number of electrons per reaction |

# 1. Introduction

During the last decade, the electric vehicle industry has been developed rapidly due to the associated environmental impacts arising from the use of conventional fossil fuel-based ICE. This transition to sustainable mobility presents several positive effects for the environment including air quality improvement, noise reduction, and fuel independency in the case of RES utilisation. The main scope of this research was the analytical examination of the prospects of light-duty hydrogen-based urban mobility from the infrastructure perspective. The contents of this dissertation include three main sections. The first introduces the problem statement, the motivation and the aims and objectives of the research, described through the RQs. The second section includes the description of the methodology followed to analyse the aspects related to the stated RQs and finally the third comprises the results of the investigated aspects aiming to provide an overall assessment of the light-duty hydrogen vehicle infrastructure that could be implemented in urban environments.

## 1.1 Background and motivation

Nowadays, hydrogen can be used in a wide range of applications, where fossil fuels dominate. Nevertheless, the fact that hydrogen does not exist in its molecular form in nature makes essential its efficient production. Although there are several available methods for producing renewable hydrogen, such as through biomass fermentation or gasification and water photolysis, the most mature one comprises water electrolysis (Hosseini and Wahid, 2016; Penconi et al., 2015). Electrolytic hydrogen presents significant advantages over other widely used methods of energy storage such as batteries because it allows storage of large energy amounts, up to GWh, for a long period of time. Hydrogen energy storage in conjunction with its ability to be transported as compressed gas or liquid makes it an emission-free alternative to conventional fuels used in the transportation sector and/or the electricity generation market (Kavadias et al., 2018). However, the high cost of producing, storing and using hydrogen as transportation fuel or in the electrical power sector consists of a significant factor for its establishment in areas where other RES technologies could be implemented (Apostolou, 2020a).

The background and motivation of this study can be described through the analysis of the energy and environmental aspects of this research problem (Fig. 1.1).

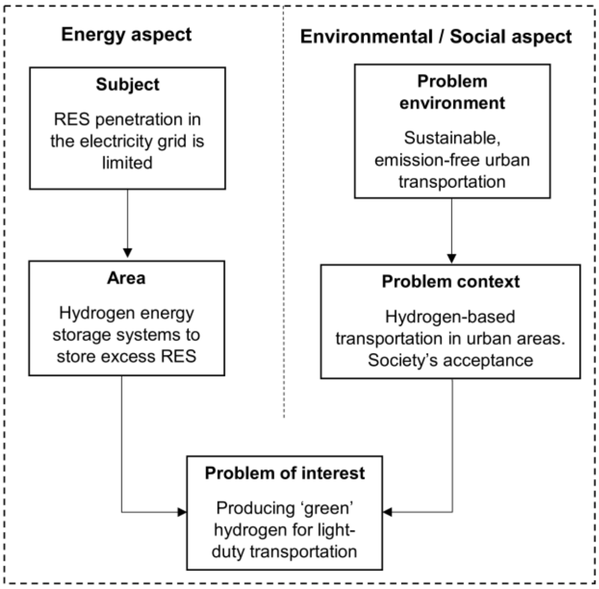



Fig. 1.1. Representation of the research background and motivation aspects.

Fig. 1.1. indicates the different aspects of the problem from an energy and environmental/social perspective and how these areas are combined together pointing out the problem of interest to be studied.

### 1.1.1 The problem's energy aspect

#### 1.1.1.1 The subject

The ongoing increase of the power capacity of RES, including mainly wind and solar energy converters, poses a challenge to the electricity grids in integrating their energy production, which is inherently intermittent (Conlon et al., 2019; Huang et al., 2019). The dynamic operation of RES power systems, together with an increase of their cumulative capacity due to the targets set by EU countries in the '2030 climate and energy framework' (a share of 32% of gross final consumption by 2030), suggests the difficulties that the TSOs will have to cope with in the years ahead (Child et al., 2019; European Commission, 2020a).

Several researchers have studied the transition to high shares of RES in the European electricity grids, suggesting various methods for supporting a RES-based electricity system. Among others, grid expansion and energy storage have been identified by (Rasmussen et al., 2012), while Kavadias et al. (2018) supported that energy storage and demand side management could play a significant role in managing RES intermittency, allowing for higher RES integration (Kavadias et al., 2018). Becker et al. (2014) suggested that the transmission capacity for harvesting 90% of the RES potential in Europe should be quadrupled, while Rodriguez et al. (2014) argued that additional cross-border interconnection investments between European countries would reduce the need for power balancing in the case of high RES capacity in the energy mix (Becker et al., 2014; Rodríguez et al., 2014). In the same context, Brown et al. (2018) presented two prerequisites for allowing high shares of RES in the European electricity mix: 1) Energy storage, including power-to-gas units, electric mobility and long-term thermal energy storage, and 2) upgrade and expansion of the cross-border interconnection of the European electricity grids (Brown et al., 2018).

Among all EU-28 countries, Denmark is one of the few with a significant RES share in electricity consumption, reaching more than 60% in 2017. Fig. 1.2 shows the RES and electricity import/export shares in total consumption in EU-28.

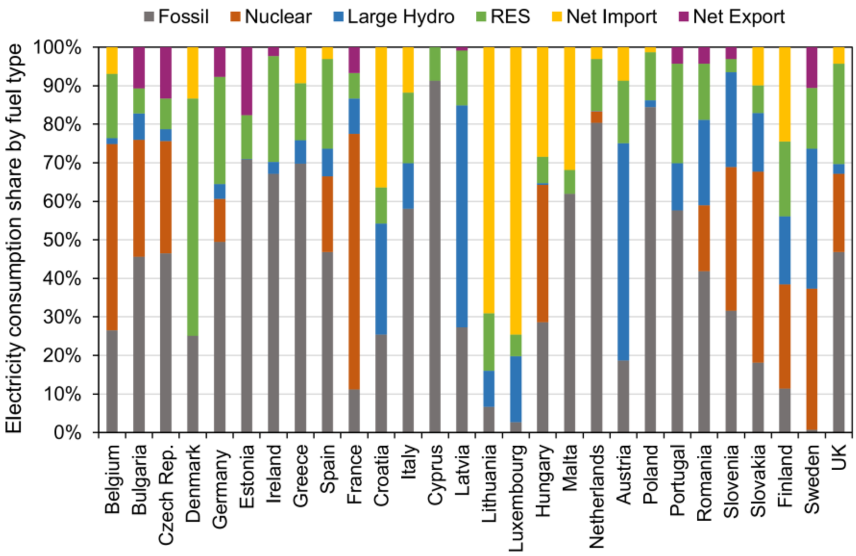



Fig. 1.2. Shares of electricity consumption by fuel type in EU-28 countries in 2017. Based on (Eurostat, 2019a).

According to the figure above, most European countries present low RES shares in their final electricity consumption, and they mainly rely on fossil fuel and nuclear-based electricity production. It is also apparent that most countries import electricity from cross-border transmission lines to meet their electric demand. Excluding the share of large hydropower plants in Fig 1.2, Denmark presents the highest share of RES in the final electricity consumption and the lowest share of fossil fuels among the countries with no nuclear-based electricity production and imports lower than 30% of their final consumption.

The high share of RES in electricity consumption in Denmark is, on the one hand, due to the high wind power capacity and the good wind potential, and, on the other hand, because of the well-structured transmission interconnections with Germany, the Netherlands, Norway and Sweden. These interconnections allow the export of electricity in the case of high RES production and low demand and vice versa (Aziz and Huda, 2019). However, there have been cases since 2008, where the annual balance of electricity imports-exports leaned towards the import side (see Fig. 1.3), suggesting that the interconnection of the transmission network limits the further increase of the RES grid penetration (Unger et al., 2018). The rising trend in electricity imports in Denmark during the last decade, compared with a decline in exports, although electricity production from wind power increased (see Fig. 1.3), indicates the necessity of implementing topologies allowing higher RES penetration in the electricity grid.

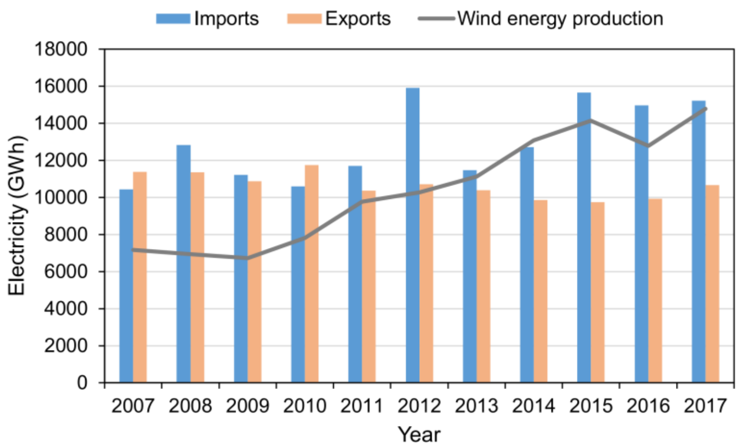



Fig. 1.3. Wind energy production and import-exports of electricity in Denmark from 2007 to 2017. Based on (Energinet, 2019).

#### 1.1.1.2 The area

Among all energy storage technologies, hydrogen-based storage presents significant benefits for long-term bulk energy storage (Kavadias et al., 2018), and according to Apostolou and Enevoldsen (2019), the financial costs of a hydrogen plant are considerably lower than other RES storage technologies with the exception of the pumped-hydro storage. Apostolou and Enevoldsen (2019) also reviewed the prospects of wind energy storage and presented the positives and drawbacks of wind-hydrogen energy storage topologies over the last two decades (Apostolou and Enevoldsen, 2019).

Lyseng et al. (2018) investigated a power-to-gas system in Alberta, Canada, allowing penetration of RES in 80% of the grid by 2050. The simulated data showed that the RES capacity could be reduced by 23% and curtailments by 87% through the implementation of hydrogen production units such as PEM electrolysers. In this study, the produced hydrogen ranged from 1% to 20% of the current annual global electrolytic production and could be successfully injected into Alberta's NG grid (Lyseng et al., 2018). Colbertaldo et al. (2019) presented a simulation of the Californian power system with increased RES penetration. The study concluded that in order to have a network in California based entirely on RES, a large capacity of solar and wind converters along with an appropriate energy storage system is required to be installed. The research focused on hydrogen storage and re-electrification via a FC. The optimisation algorithm resulted in capacities of 37, 80, 77 and 33 GW of PVs, wind power, water electrolysis and FCs systems, respectively (Colbertaldo et al., 2019). Weidner et al. (2018) also demonstrated the prospects of using hydrogen for power-to-mobility and power-to-power schemes in Germany, Belgium and Iceland. According to the presented levelised cost analysis, the price of hydrogen fuel produced from water electrolysis to secure a viable business case would range from 5.96 to 8.55 €/kg$H_2$ depending on the country and the scale of the system, showing a comparable price to that of conventional fuels. The power-to-power scenario included hydrogen production from excess RES via water electrolysis and repowering of the stored energy back to the grid through FCs during electricity shortages. For large systems, the authors concluded that the cost of selling electricity would exceed 500 €/MWh and expected to drop to 300 €/MWh, which compared to other technologies is considered to be high (Weidner et al., 2018).

Alshehri et al. (2019) documented the utilisation of hydrogen systems, including water electrolysis and FCs in providing ancillary services to electricity networks. The authors simulated four scenarios of the electricity network in the northern region of the Netherlands, including a base scenario (current operation) and a scenario with water electrolysis and FCs used for frequency control. A simulated reduction of the rotational inertia resulting to a steeper drop of the frequency was countered by the inclusion of the hydrogen-based topologies that improved the value of the lowest frequency (i.e. frequency nadir) up to more than 0.15 Hz, suggesting the technical benefits of FCs in the frequency balancing markets (Alshehri et al., 2019).

Based on Mehrpooya et al. (2019), the characteristics of high temperature hydrogen technologies (i.e. solid oxide FC/electrolyser) also make them ideal for tri-generation of hydrogen, power and heat. In their research, the authors presented the optimal operating point of a 500 kW net output power system in terms of efficiency and cost evaluation. The results showed a FC power capacity of 633.4 kW, an electrolysis power capacity of 166.4 kW, a hydrogen production rate of 5.64 kg/h and a heat recovery of approximately 34 kW (Mehrpooya et al., 2019).

Nagasawa et al. (2019) investigated the use of wind-produced hydrogen to meet the potential hydrogen demand of light-duty vehicles in the USA and the state of Texas. The model proposed by the authors provided results concerning hydrogen production with a maximum profit. Calculation of the marginal price of hydrogen showed values of approximately 3.6 €/kg$H_2$ for an economical operation of the system. Low hydrogen prices (e.g. 0.9 €/kg$H_2$) indicated that hydrogen production is only favourable in the morning when electricity prices are lower (Nagasawa et al., 2019).

Shabani and Moghaddas-Tafreshi (2020) studied a multi-purpose hydrogen system supporting thermal, electrical and hydrogen loads. The system consisted of an electrolyser, a FC, a PV generator, a battery electric storage, an anaerobic digestion reactor, a hydrogen and thermal storage, and auxiliary power electronics. The authors simulated the operation of the system to cover specific loads when a decentralised unit was connected to the electrical grid and then compared it with a respective centralised unit in terms of social welfare and financial profits for private ownership. The results indicated that social welfare with the centralised unit is advantageous than the decentralised unit, while the economic assessment showed higher profits for the decentralised unit (Shabani and Moghaddas-Tafreshi, 2020).

The ability of hydrogen technologies to be used in many applications was assessed by Widera (2020), who reviewed and compared hydrogen production methods in terms of their respective environmental impacts and costs. The analysis of various case studies revealed that by 2050, hydrogen technologies for the integration of large RES capacities into the electricity networks would play a critical role, supporting simultaneously the mobility and the building sectors (Widera, 2020).

### 1.1.2 The problem's environmental aspect

#### 1.1.2.1 The problem environment

Since the beginning of 1990, the UN have identified the impacts of climatic change occurring due to the profligate exploitation of finite energy sources and have committed to decrease the GHG emissions by 18% compared to the 1990 levels by 2020 (United Nations, 2020). The EU-28 respective targets were set to 20% and 40 % reduction of the GHG emission from the 1990 levels by 2020 and 2030 respectively (European Commission, 2020a). The new EU 'Green Deal' initiative consisting of a roadmap towards tackling climate change was presented late 2019 and focussed on actions required to implemented by EU to be carbon neutral by 2050 (European Commission, 2019a). Based on Fig. 1.4, the GHG emissions in EU-28 for 2018 were decreased by 20.7% compared to 1990 levels indicating that the 2020 target was reached. However, transportation induced GHG emissions were increased at the same time by approximately 20% compared to 1990 levels accounting 21.6% of total GHG emissions (Eurostat, 2020a). The EU 'Green Deal' suggests a reduction of 90% of current mobility-induced emissions by 2050 through adopting different modes of transport (i.e. rail and water) and by boosting the supply of sustainable alternative transport fuels. Moreover, the transportation policy of the EU 'Green Deal' quoted that the requirements on new alternative fuel and recharging stations by 2025 would be a seventhfold increase from current station numbers (European Commission, 2019a).

Hence, it is apparent that for meeting the 2050 transportation emission targets suggesting a 60% reduction compared to 1990 levels (European Environment Agency, 2020), no- to low-emission vehicle technologies and infrastructure should be extensively implemented.

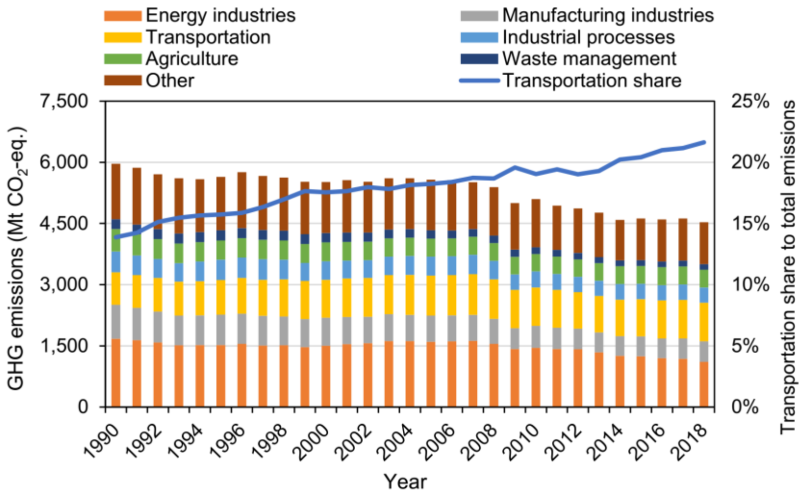



Fig. 1.4. EU-28 GHG emissions by sector between 1990 and 2018. Based on (Eurostat, 2020a)

Among all means of transportation, road transportation in EU-28 presents the highest share in GHG emissions reaching 93.7% of total transport (898.89 out of 950.05 Mt $CO_2$-eq.) from which approximately 40% is estimated to come from urban transportation (European Environment Agency, 2020; European Union and Interreg Europe, 2018). To this end, urban transportation induced emissions constitute an important factor affecting global climate change mitigation and thus is significantly studied in the recent international peer reviewed literature.

Cheng et al. (2015) investigated urban transportation policies to reduce the $CO_2$ emissions in the city of Kaohsiung in Taiwan. The authors used a system dynamics model to simulate a real urban transportation system and evaluated how parameters such as $CO_2$ emissions altered by the dynamic behaviour of factors such as population and vehicles numbers. The outcome of their study indicated that policies including increased fuel tax, and setting a strict motorcycle parking management would reduce emissions by 9.9%, and 5.1% respectively (Cheng et al., 2015). Likewise, Sun et al. (2020) evaluated how control policies including vehicle population constraint, public transportation promotion, new energy vehicles, and shifting freight traffic from highways to railways and waterways could mitigate $CO_2$ emissions in a middle-size city in China. The outcome showed that all these policy measures would reduce future $CO_2$ emissions, with the most significant reduction reported to occur through the freight traffic optimisation for the CO, $NO_x$ and $PM_{10}$, and the vehicle population constraint for the volatile organic compounds (Sun et al., 2020).

Yuan et al. (2019) presented a study of the evolution of urban transportation induced emissions in China and the factors contributing to their increase. The growth of private vehicles number compared to public transportation along with the GDP growth, were found to pose a negative impact to the urban emissions in seven cities. For example, Beijing presented an increase of annual emissions between 2004 and 2014 by approximately 11 Mt of $CO_2$, mostly due to the private vehicle fleet growth. The authors concluded that the introduction of 'green' and low-carbon urban transportation would be important in order to reach the target set by the Chinese government to reduce $CO_2$ per unit GDP by 60% - 65% from the 2005 level (Yuan et al., 2019).

Li and Yu (2019) presented in their research a forecast concerning the evolution and peak of $CO_2$ emissions from urban transportation in China. The model used by the authors assessed how the introduction of low-carbon measures such as shifting to alternative 'green' vehicles could alter the $CO_2$ emissions trend. The results indicated that car urban emissions account for 60% of total transport emissions suggesting that replacing conventional vehicles with contemporary technologies of alternative clean fuel or with improved fuel efficiency counterparts could contribute to a peak of $CO_2$ emissions between 171 and 214 Mt at around 2020 (Li and Yu, 2019).

The replacement of conventional vehicles by EVs in Beijing, China was also found by Kolbe (2019) to reduce vehicles' fuel combustion $CO_2$ emissions and the associated emission from air condition systems operation. The author examined two EV concepts including BEVs and FCEVs, which presented the highest $CO_2$ reduction in the case of using wind generated electricity and 'green' hydrogen fuel, respectively. Using a regular energy mix for the recharging and hydrogen generation processes was found to lower emissions but this reduction was less compared to a scenario of enhanced metro transportation (Kolbe, 2019).

Breuer et al. (2020) used a bottom-up approach to estimate the road transport emissions in urban areas of the North Rhine-Westphalia in Germany aiming to determine how the transportation sector should transform in terms of alternative vehicle technologies and different fuels. The results indicated that 91% and 9% of $NO_x$ emissions and 71% and 29% of $PM_{10}$ emissions are coming from diesel and petrol vehicles, respectively. The potential reduction of these emissions by replacing the conventional vehicle technologies with either BEVs or FCEVs was found to be 65% and 11% for the $NO_x$ and $PM_{10}$ respectively (Breuer et al., 2020).

The benefits of adopting EVs in urban transportation in terms of reducing emissions was assessed by Siskova and van den Bergh (2019). The authors investigated how city activities contribute to overall emissions and concluded that among others, shifting from conventional vehicles to EVs charged from RES-based energy mix, emissions could be threefold reduced compared to a scenario of a conventional vehicle fleet. However, it was stated that in the case of a fossil-fuel based electricity mix, the emissions reduction would be diminished (Siskova and van den Bergh, 2019).

Krause et al. (2020) studied the prospects of road transport decarbonisation and the $CO_2$ emission reduction that could be achieved in EU by 2050. The research was based on the assessment by a group of experts of potential transportation measures aiming to reduce future emissions. Three SCs of road vehicle technology composition were examined including: a) a maximum market penetration of BEVs and PHEVs, b) an inclusion of FCEVs in the first SC, and c) a mixed composition of lower electrification, no FCEVs and conventional vehicles dominating in the mix. The results showed that $CO_2$ emissions could be reduced by 85%-90% and 40% compared to 1990 levels, for the two optimistic and the third pessimistic SC respectively (Krause et al., 2020).

A comparison between the LCA of light-duty alternative vehicles in urban environments was presented in a research published by Marmiroli et al. (2020). The authors compared three different powertrain topologies of commercial vehicles including diesel, NG, and electric in identified impacts including depletion of fossil fuels, acidification and global warming. The outcome showed that the electricity-based powertrain provided savings in all categories associated with fuel combustion even if the energy mix was based on fossil fuels. However, it was quoted that EVs present higher impacts compared to NG and diesel powertrains in photochemical oxidation, eutrophication and acidification (Marmiroli et al., 2020).

A part of the international peer-reviewed literature quoted in this section investigated the prospects of reducing the transport-induced GHG emissions in China through the adoption of ‘green’ vehicle technologies. It is documented that transportation emissions in large Asian markets such as China could be significantly decreased by the integration of AFVs and EVs. During the last years, China’s policy to support EV technology (Hsieh and Green, 2020) resulted to a great contribution in the global market with 2019 and 2020 sales exceeding 2.5 million vehicles and accounting more than 50% and 40 % of the global EV market respectively (EV-volumes, 2020). The recent policy of China to impose a mandate to auto-manufacturers concerning the production of EVs to reach 40% by 2030 will expand significantly the EV market as it is expected that it will bring down worldwide cost of batteries and vehicles (Stauffer, 2020).

#### 1.1.2.2 The problem context

Based on the above, it is apparent that one of the most promising solutions towards the mitigation of urban transportation emissions is the replacement of the conventional vehicle fleet with alternative-powered vehicles including EVs. EVs consist of three main powertrain technologies: BEVs, PHEVs and FCEVs. Among these, PHEVs are low emission vehicles, while BEVs and FCEVs present zero direct GHG emissions (McKinsey & Co, 2010). Apostolou (2020b) suggested that light-duty EVs for urban transport such as scooters and bicycles are a feasible alternative to larger vehicles as they present better environmental footprint and comparable ownership costs (Apostolou, 2020b). The two powertrains with zero direct emissions (i.e. BEVs and FCEVs) present advantages and drawbacks once compared between each other. Bicer and Dincer (2017) compared FCEVs with BEVs and methanol-fuelled vehicles in a LCA analysis. Their results indicated that FCEV technology presents lower global warming potential than its counterparts (Bicer and Dincer, 2017). Thomas (2009) in his study suggested that the fossil-fuel energy mix in many countries would have an environmental impact during the charging processes of BEVs, resulting to a lower LCA carbon footprint of the FCEVs, especially in the case of using by-product hydrogen fuel from the chemical industry (Thomas, 2009). In the same context, Li et al. (2016) compared the environmental prospects of both BEVs and FCEVs concluding that the powertrain with more environmental benefits depends on the electricity mix and the methods used to produce and subsequently store the hydrogen fuel (Li et al., 2016). Likewise, the energy mix for producing hydrogen from water electrolysis was framed by Kolbe (2019) as being an important factor in evaluating the carbon footprint of FCEVs. The results showed that a regular energy mix contributes to less environmental benefits of FCEVs compared to AFVs (Kolbe, 2019). Kim et al. (2020) suggested however that in S. Korea the exclusion of FCEVs from the vehicle mix in 2030, would result to an increase of GHG emissions although the BEV market share would be higher (Kim et al., 2020).

Acknowledging the above, hydrogen-based light-duty vehicles such as scooters and bicycles could play a significant role on one hand in the decongestion of urban traffic and on the other in a better environmental performance compared to larger alternative vehicles. Brey et al. (2018), Apostolou and Xydis (2019) and Apostolou (2020b) indicated that FCEVs also present similar to conventional vehicles values of driving range and refuelling times suggesting that this type of EV is a considerable candidate in the future urban vehicle mixed fleet (Apostolou, 2020b; Apostolou and Xydis, 2019; Brey et al., 2018).

Reichmuth et al. (2013) suggested that by replacing 40% of the light-duty vehicles with FCEVs in USA in conjunction with an optimistic biofuel production and use in conventional vehicle fleet, could be a solution of reaching a target of reducing GHG emissions of this type of vehicles by 80% compared to 1990 emissions (Reichmuth et al., 2013).

Hwang and Chang (2010) compared the environmental performance of BESs and FCESs in Taiwan under different hydrogen fuel production schemes by using as reference a conventional petrol scooter. The results showed that although the tank-to-wheel emissions where zero for the BESs and all the FCES cases, the WtW emissions of FCESs were found to be significant if hydrogen fuel is produced from water electrolysis powered from the electricity grid. On the other hand, if a water electrolysis system is powered from RES such as PVs, WtW GHG emissions are reduced to minimum (i.e. less than 5 $gCO_2$-eq./km) (Hwang and Chang, 2010).

Tso et al. (2012) published the results of a FCES program in Taiwan for coping with the intense air pollution in urban areas. The outcome of their experimental study showed that FCESs would help in reducing urban emissions, though several problems occurred during the experimental phase such as low drivetrain endurance and issues with the MH storage system at low ambient temperatures (Tso et al., 2012). Similarly, Shang and Pollet (2010) tested the operation of a FCES in Birmingham, UK and compared the results with a BES and a petrol scooter. The results included a WtW $CO_2$ emission analysis indicating a value of 9.37 $gCO_2$/km in the case of wind-produced hydrogen fuel, while the BES presented a $CO_2$ footprint of 24.07 $gCO_2$/km under a normal energy mix (Shang and Pollet, 2010). A SWOT analysis for the development of FCESs in Taiwan was published by Hwang (2012). The author used as input to the analysis, the energy density and GHG emissions of FCESs, BESs, and petrol scooters. The results showed that FCES drivetrain performed better in energy consumption and GHG emissions per km compared to its counterparts with 123 Wh/km and 23 $gCO_2$-eq/km (Hwang, 2012). Likewise, Chang et al. (2016) compared the carbon footprint between a conventional an on-board SMR hydrogen, a methane SMR, a plug-in and a hybrid electric scooter. The lowest performance was found in the conventional scooter with approximately 137.8 $gCO_2$/km, while the best has been observed in the SMR and on-board SMR with a footprint of 11.5 and 11.7 $gCO_2$/km respectively (Chang et al., 2016).

Mellino et al. (2017) compared BEBs with FCEBs in an LCA perspective. The LCA was performed under the same distance range of 100 km and the results showed that although the FCEB performed worst in the production phase due to the complexity of the powertrain components, the emission footprint of the BEB was worst during the operating phase (Mellino et al., 2017). The prospects of PV-based hydrogen fuel production for a FCEB sharing program in Italy were presented by Minutillo et al. (2018). The authors proposed a sustainable energy chain including a 103 kW PV power plant and a 16 kW alkaline electrolyser able to annually produce 2,190 kg of hydrogen fuel. The annual travelling distance equalled to 3,772 km contributing to an avoidance of 490 kg of $CO_2$ emissions (Minutillo et al., 2018).

The obvious environmental benefits arising from the adoption of alternative fuel vehicles and specifically FCEVs in urban environments could be deemed as the keystone for coping with the environmental impacts associated to conventional transportation. However, a factor playing a significant role in the transition to sustainable urban transportation is the social acceptance of new mobility technologies.

Iribarren et al. (2016) studied the prospects of hydrogen transportation from a social perspective in Spain. The authors' methodology consisted of a quantitative approach based on empirical data gathered from a survey focussing on the technology awareness, the costs and the required infrastructure. Although the results were based on a sample of relatively young participants (<35 years old), it is indicated that technology knowledge was high but the increased costs and limited infrastructure negatively affected the willingness of the participants to adopt this technology in the short term (Iribarren et al., 2016).

In the context of the transition from conventional vehicles to AFVs, Hackbarth and Madlener (2016) documented the level of public acceptance of AFVs in Germany. The results of their research showed that the German public is not homogeneous in regards to consumer's perspective. The distinct groups were identified among others as 'PHEV enthusiasts', 'purchase price sensitives', and 'fuel cost savers'. The outcome indicated that tax exemptions and non-monetary governmental incentives could enhance the AFVs market, while fuel cost reductions were not valued as much as expected from the consumer's side to strongly favour the expansion of the market (Hackbarth and Madlener, 2016).

Itaoka et al. (2017) investigated the awareness, perception and acceptance of hydrogen-based transportation. The published results compared to older relative studies performed in Japan showed that there was a small improvement in regards to the knowledge of the technology and people were more positive toward the adoption of this mobility option. However, increased awareness resulted to a more cautious public about the risks and benefits of the technology adoption (Itaoka et al., 2017).

Wang et al. (2018) presented the results of an empirical study concerning the acceptance of EVs by the public in Shanghai, China. The authors concluded that public's willingness to replace their conventional vehicle with an EV alternative was low and was highly dependent on the educational level and income of the participants. Consumers with secondary and lower educational level, and low income responded not to be willing to invest in an EV, while consumers with higher income and graduate education level were considering EVs to replace conventional vehicles (Wang et al., 2018).

The prospects of electric-based transportation in Malaysia were assessed by Asadi et al. (2021). The paper studied the propensity of the public to purchase an EV through a survey focussing on factors affecting the consumer's attitude toward the transition to 'green' transportation. The results indicated that 'personal norms' suggesting the moral commitment of the individual for environmental friendly technologies poses significant effect on the intention to adopt EVs. 'Awareness of consequences' of using conventional vehicles affected positively 'ascription of responsibility', which in turn affected positively the 'personal norms'. Therefore, it is documented by the authors that environmental awareness consists of a significant factor for the transition to sustainable transportation (Asadi et al., 2021).

In the same context, Cui et al. (2021) investigated the consumers' purchase motivation for EVs in China based on different human needs that play a significant role in the decision-making processes. The results presented, showed that environmental concern is the most significant factor in EV adoption followed by price consciousness, social influence, openness to experience, and self-esteem. All factors except price consciousness were found to positively affect the purchase motivation of EVs in China, indicating that the environmental and social aspect of the transition to new 'green' transportation technologies are a significant parameter to be taken into account for the policymakers and stakeholders (Cui et al., 2021).

### 1.1.3 The problem of interest

The presented context of the under-investigation problem revealed that the key interest of this research topic is the sustainable production-storage and delivery of hydrogen to light-duty vehicles in urban areas in order to cope with the respective indisputable GHG pollution. Although there is a significant amount of research articles in the international literature concerning HRSs, urban located HRSs and particularly those able to additionally provide 'green' hydrogen refuelling processes to light FCEVs such as FCESs and FCEBs are not adequately studied.

Urban located HRSs for FCEVs are considered to present higher risks compared to conventional refuelling stations. Gye et al. (2019) presented a quantitative risk assessment of high-pressure HRS located in an urban area in order to evaluate the main associated risks from the implementation of such stations in density populated city centres. The results indicated that the main risks might be found in the compressor and dispenser systems, which need to be installed with an additional safety barrier to prevent continuous release of hydrogen in the case of leaks (Gye et al., 2019).

Campíñez-Romero et al. (2018) proposed the introduction of urban HRSs to support a FC taxi fleet as a start-up hydrogen supply infrastructure. The results of their research indicated that a capital of $415 million along 25 years through public funding would provide during a development period of six years, an adequate network of 112 HRSs able to meet the fuel demand of 15,000 FC taxis in the city of Madrid, Spain. The estimated $CO_2$ emission annual reduction would reach 300 kt (Campíñez-Romero et al., 2018). Likewise, Micena et al. (2020) studied the implementation of an urban PV-powered HRS for replacing an existing taxi fleet in the Brazilian city of Guaratingueta by FC taxis. The authors documented that 185.4 $kgH_2$ are required to meet the entire fuel demand with a hydrogen fuel cost between 8.96 and 13.55 $/$kgH_2$ (Micena et al., 2020).

Kovač and Paranos (2019) published an experimental study of the operation of a FCEB in Zagreb, Croatia, refuelled from a small PV-based refuelling station with hydrogen outlet flow of 2,000 cc/min. The authors quoted details on the operation of the FCEB in terms of autonomy and hydrogen consumption (i.e. approximately 66 km and 4.5 $gH_2$ respectively), while the respective refuelling station was able to provide hydrogen fuel for five bicycles in a daily basis (Kovač and Paranos, 2019).

## 1.2 Aim and objectives

The analysis of the background of this study indicated that a multi-dimensional hydrogen market including among others the energy and transportation sectors is emerging. RES-based hydrogen could serve as a potential large-scale energy storage topology that could provide clean fuel in a LC timeline to both electricity production and mobility. Hydrogen infrastructure and particularly HRSs for passenger vehicles including cars and busses can be quoted to currently present a significant investment cost with the majority of stations ranging between €1.5 and €3.5 million depending on the type, and capacity (Apostolou and Xydis, 2019). To this end, investments of HRSs able to accommodate FCEVs with a fuel demand similar to the one of their contemporary conventional counterparts could be characterised as unappealing for a market that is currently at an infant stage of development.

Taking all the above into consideration, there is a gap in knowledge regarding the infrastructure investment opportunities arising from the implementation of light-duty FCEVs in urban environments. Hence, the aim of this project focussed on the investigation of 'green' hydrogen production, storage and utilisation SCs for light-duty transportation in urban environments. The purpose of the analysis of those SCs was the identification of the best business case of hydrogen infrastructure required to support a future fleet of light-duty FCEVs such as FCEBs and/or FCESs in terms of CAPEX, O&M costs and dispensed hydrogen fuel costs. The investigated SCs aimed at locating the lowest financial investment from the infrastructure investor's side with at the same time securing the best fuel price for the future customers.

The aim of this PhD research is further described through the frame of objectives in order to assess the prospects of the light-duty hydrogen vehicles refuelling market.

- Identification of the socio-economic parameters affecting the transition to hydrogen mobility.
- Investigation of a hydrogen production and storage unit that will include a hydrogen generator, a compression, and a dispensed stage to refuel FC light urban vehicles.
- Investigation of the viability of such system by estimating CAPEX, O&M cost, energy cost, and range of the vehicle.
- Development of a model for the short-term prediction of hydrogen production based on the characteristics of the hydrogen production-storage unit. Integration of the model into the pricing mechanisms of the electricity market.
- Study and analysis of the emerging market regarding the cost benefit of both wind farm and hydrogen light urban mobility scale refuelling infrastructure investors to secure at the same time the lowest possible hydrogen fuel cost.
- Techno-economic assessment of different types of HRSs for meeting the fuel demand of FCEBs in an urban area.

The above-mentioned objectives can be described by the following RQs:

*1. What are the socio-economic prospects of the light-duty FCEVs' private transportation and its respective infrastructure?*

The first RQ seeks to explore the prospects of hydrogen mobility both from the social and financial point of view. It also deals with the first and second objective of the research aiming to identify the social factors affecting the hydrogen market development, the different types of HRSs and their respective economic parameters. Moreover, the social acceptance of such technologies has been deemed highly significant towards the light-duty passenger FCEVs and infrastructure market development.

*2. Why and how a 'green' hydrogen production system participating in wind power and electricity markets could be a viable solution towards sustainable light-duty hydrogen transportation?*

RQ2 was set to ensure if a hydrogen production system coupled to wind energy and/or the electricity market could be a financially feasible case to support a hydrogen light-duty refuelling market. This RQ aimed at finding answers regarding the economic benefits from the wind farm (i.e. by avoiding energy waste) and the hydrogen infrastructure (by gaining income from both selling hydrogen fuel and participating in the electricity market) investors' perspective.

*3. Which type of hydrogen refuelling infrastructure for cycling-based transportation is the most economically feasible solution from an investor and customer perspective?*

The scope of the third RQ could be defined as the identification of the best techno-economic SC for the hydrogen infrastructure market in regards to light-duty urban FCEVs. The hydrogen transportation market development is often characterised by the 'chicken and egg' dilemma, suggesting the two-way relationship between hydrogen infrastructure and FCEVs (Campíñez-Romero et al., 2018; Ogden et al., 2014); the lack of adequate infrastructure hinders the FCEVs market and vice versa. The acceptance of this transport technology by the public is quoted to be influenced apart from economic factors by the accessibility to the relevant refuelling infrastructure. Therefore, a limited number of HRSs poses a negative effect on the public's willingness to purchase a FCEV. Moreover, investments on hydrogen refuelling infrastructure is highly dependent on the demand of the hydrogen fuel. Low demand of the fuel induces either high fuel prices or limited future investments or both. Hence, it is apparent that the expansion of this market is required to be financially assessed from both the HRS investor and the vehicles owners' perspective.

The next chapters of the dissertation focussed on the thorough investigation of the stated RQs, firstly by configuring the appropriate methodology to be implemented and secondly by presenting and discussing the results answering the respective RQs. The acquired results analysing the stated problem of interest were presented through respective publications in international peer-reviewed literature quoted in the following sections.

# 2. Methodology

The methodological approach of this research is described in this section, which initially introduces the main approach leading to the final research design of this dissertation. Following the research design, a presentation of the applied methodology in the quoted articles is documented and discussed. The main dimensions considered during the methodology development included the research philosophy and reasoning, and the research data.

## 2.1 Background theory

The research dimension named 'philosophy' consists of the philosophical stance of the researcher and is considered to be subjective. According to Sutrisna (2009), the philosophical stance of a researcher does not require justification and that is why the title PhD abbreviates '*Doctor of Philosophy*' and not '*Doctor in Philosophy*' (Sutrisna, 2009) indicating that a researcher is required to demonstrate a thorough understanding of the philosophical issues in the context of his/her scientific field. The two main philosophical concepts namely the ontology and epistemology describe the philosophical stance of a researcher and consequently affect the reasoning of the research (Sutrisna, 2009).

The reasoning of the research describes the logic behind the study. It is based on the background of the study, the existing knowledge and provides the general approach of how the research should be designed. The two main types of research reasoning comprise the deductive and inductive research. On the one hand, in deductive research, hypotheses are formulated based on an analysis of the existing literature. Identification of knowledge areas that are inadequately studied results in the formation of the stated RQs in a '*If…then*' relationship that is either confirmed or rejected by the acquired results. On the other hand, inductive research begins with the identification of the general problem based on existing theory and observation and seeks to find the possible results to the problem of interest by collecting data in order to answer the stated RQs (Jonker and Pennink, 2009).

The identification of what type of research data should be adopted during the research design process is crucial for the completion of a scientific research, as it constitutes the main input to the methodology application used to find the answers to the problem of interest. The two types of data that are usually gathered and analysed in research studies include the quantitative and qualitative data. A quantitative approach is about gathering factual data that can be quantified and analysed to provide the results of the under-investigation problem. The researcher is the neutral observer who although examines the phenomena occurring during the research process, he/she is as objective as possible acting independently in the data assessment (Jonker and Pennink, 2009; Sutrisna, 2009).

A qualitative approach, as its name indicates, deals instead of the factual characteristics, with the quality of the under investigation phenomena (Sutrisna, 2009). A qualitative method involves mostly linguistic sources of data such as surveys or interviews seeking to interpret phenomena from the perspective of the subjects involved. In qualitative data acquisition, the researcher should be unprejudiced in order to achieve the best evaluation of the results without introducing biased conclusions (Jonker and Pennink, 2009).

The combined use of quantitative and qualitative approaches for achieving valuable insight and comprehension of the under investigation problem is called multi-method research approach (Jonker and Pennink, 2009). The multi-method approach, often cited as mixed-method research, established in the early 2000 and evolved in correspondence to overcome the limitations of quantitative and qualitative methodologies (Lund, 2012). These limitations might include difficulties in generalisation and duplication, and utilisation of immaterial hypotheses and swallow descriptions for the qualitative and quantitative methods respectively (Caruth, 2013). The most common multi-method approaches used in academia include among others (Creswell and Guetterman, 2019):

- The convergent parallel, where quantitative and qualitative data are simultaneously collected.
- The explanatory sequential, where quantitative data are initially gathered followed by qualitative to enhance the findings.
- The exploratory sequential, where qualitative data are gathered to examine a topic and quantitative to explain the qualitative findings.
- The multiphase, where the problem of interest is investigated through a series of studies.

## 2.2. Research design

The identified problem of interest of this PhD research project and the emerged aim and objectives as described by the stated RQs in section 1.2 are showing a multi-dimensional perspective of the subject. Apart from the technological and financial aspects of the problem that need to be investigated in order to find a viable SC that could be integrated in the already existing vehicle refuelling market, there is an important factor that substantially affects all new technologies entering into a commercialised stage of development.

Social acceptance of new technologies has been quoted as one of the most significant key issues in peer-reviewed literature showing that the opinion of the public for new technologies plays a significant role in the development of new markets (Assefa and Frostell, 2007; Cohen et al., 2014; Niehaves et al., 2012;

Pantano and Di Pietro, 2012; Schepers and Wetzels, 2007). In this context, the social perspective regarding a hydrogen refuelling infrastructure market for urban light-duty FCEVs consists of a major parameter in the investigation of the prospects and the features characterising this market. To this end, the multi-method research approach has been selected to be the most appropriate method for meeting the objectives of this research through the implementation of the different data acquisition and analyses in the respective articles presented in the next sections of this dissertation. Hence, among all various approaches of multi-method research methods, the multiphase type suggesting the examination of the research problem through a number of studies was assessed to be the prevailing general methodology to ensure an in-depth investigation of the identified aim of this research.

Acknowledging the above, the main core of the methodology adopted to meet the aim and objectives and answer the stated RQs included three main research approaches. Initially, in respect to RQ1 a literature review on hydrogen transportation market was compiled to assess the state of art of the technology and secondly the prospects of hydrogen mobility in Denmark were investigated via a survey to identify the social acceptance of this technology by the Danish public. Thereafter, in the context of RQ2 and 3, an experimental section was designed to get the refuelling process data of a FCEB. The experimental part was divided in two major phases. The first phase included an investigation of low-pressure refuelling processes of a light-duty urban FCEV such as a FCEB. The laboratory refuelling system used consisted of a small-scale water electrolysis unit able to provide hydrogen of high purity at an outlet pressure of 30 bar. The gathered experimental data (i.e. quantitative data) provided results concerning energy consumption of the hydrogen generator and delivered autonomy range of the FCEB. Likewise, the second phase included the acquisition of the same data but with refuelling pressures of up to 200 bar (i.e. 100, 150 and 200 bar). The second phase of the experimental part occurred in a pilot HRS adapted to provide hydrogen fuel in a pressure range between 30 to 200 bar to small vehicles.

The results from both experimental phases were financially analysed to get an overview of the different perspectives that a light-duty urban refuelling market for FCEVs could be developed. The calculated refuelling prices based on the specifications of HRSs for low to high refuelling pressure capabilities were disseminated to potential adopters, who provided feedback on how the respective market would become attractive to end-users. Fig. 2.1 indicates a flow diagram of the applied methodology.

The gathered experimental data were used to model the operation of all the types of HRSs and in conjunction with the CAPEX, and OPEX, the hydrogen refuelling price was calculated based on a positive NPV and IRR of future business SCs.

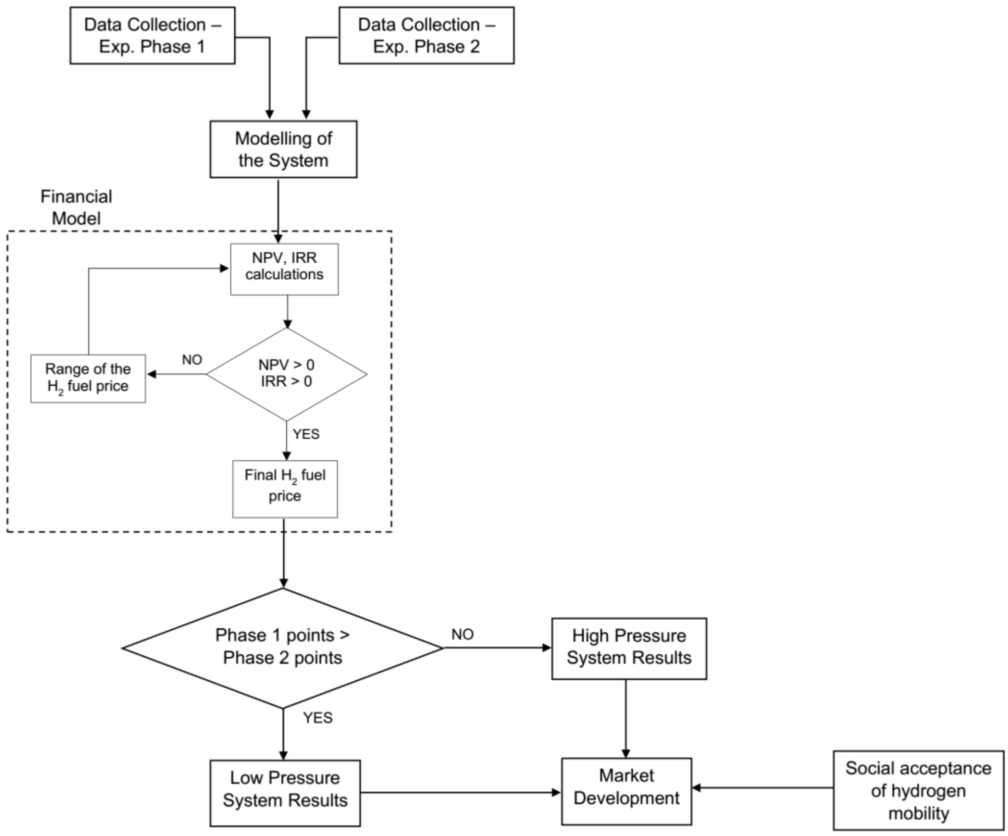



Fig. 2.1. General methodology applied towards the light-duty urban hydrogen refuelling market.

The outcome of the disseminated to future adopters hydrogen refuelling prices linked to the respective SCs was then assessed to find out which of the business SC was the most prevailing among the survey participants.

The number of research studies stemming from the multi-method approach is linked to the accomplishment of nine research tasks used to meet the objectives of the PhD project and consequently answer the stated RQs.

Task 1: Experiments of hydrogen production processes and use on a FCEB under different driving patterns and routes.
Task 2: Review of WH systems and identification of the central Denmark’s wind power status and pricing mechanisms of the spot and balancing electricity markets.
Task 3: Development of a model for short-term prediction of hydrogen production.
Task 4: Integration of the hydrogen production system into the wind power and electricity market.
Task 5: Design - Analysis of the new hydrogen production-storage-fuelling market. Integration with the developed model.

Task 6: Application of the developed model on a small-scale autonomous HRS case study in the city of Herning, Denmark. Investigation of the viability of a future attempted business integrated in the particular market.
Task 7: Identification and analysis of the social factors to affect the new market.
Task 8: Investigation of the market economic factors under a different storage technology.
Task 9: Application of the new market to broader regions – Analysis of the results.

Table 2.1 summarises the publications linked to the RQs and the respective research tasks.

Table 2.1. Journal articles presenting-discussing the results of the PhD tasks as linked to the RQs.

| RQs | Research Tasks | Title of the article | Author(s) | Journal | Year |
|---|---|---|---|---|---|
| RQ1 | - | A Literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects | Dimitrios Apostolou, George Xydis | Renewable & Sustainable Energy Reviews | 2019 |
| | 7 | Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark | Dimitrios Apostolou, Sissel N. Welcher | International Journal of Hydrogen Energy | 2021 |
| RQ2 | 2 | The past, present and potential of hydrogen as a multifunctional storage application for wind power | Dimitrios Apostolou, Peter Enevoldsen | Renewable and Sustainable Energy Reviews | 2019 |
| | 2, 3, 4 | Optimisation of a hydrogen production – storage – re-powering system participating in electricity and transportation markets. A case study for Denmark | Dimitrios Apostolou | Applied Energy | 2020 |
| RQ3 | 6 | Supporting green urban mobility – The case of a small scale autonomous $H_2$ refuelling station | Dimitrios Apostolou, Peter Enevoldsen, George Xydis | International Journal of Hydrogen Energy | 2019 |
| | 1, 5 | Assessing the operation and different refuelling cost scenarios of a fuel cell electric bicycle under low-pressure hydrogen storage | Dimitrios Apostolou | International Journal of Hydrogen Energy | 2020 |
| | 1, 5 | Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market | Dimitrios Apostolou, Pedro Casero, Vanesa Gil George Xydis | International Journal of Hydrogen Energy | 2021 |
| | 8, 9 | Refuelling scenarios of a light urban fuel cell vehicle with metal hydride hydrogen storage | Dimitrios Apostolou, | Energy Transitions (Under review) | 2021 |

The first article comprised a literature review aiming to present the current situation of the hydrogen transportation market from both the vehicles and the refuelling infrastructure perspectives. The article followed a methodology including the presentation of current HRS topologies, evolution and current status of the FCEVs and HRS and forecasts about how infrastructure, vehicles' number and hydrogen fuel cost is going to evolve by 2050. The article's contribution was not limited only to a simple representation of the quantitative gathered data but it provided an in-depth analysis of the data by presenting different SCs in regards to the prospects of hydrogen mobility market in a horizon of 30 years.

As discussed above, the social acceptance of hydrogen technologies in the transportation sector is of high importance regarding the prospects of a new hydrogen mobility and infrastructure market. To this end, the second article aimed at the identification of the social perspective on hydrogen-based transportation in Denmark and the possible reasons that may affect positively or negatively its prospects. The methodology followed included the examination of nine hypotheses linked to the identified variables posing an impact on the prospects of hydrogen urban private mobility. The stated hypotheses were either confirmed or rejected based on the answers' chi-square crosstab analyses received from a 13 questions survey.

The third article linked to task two and RQ2, consisted of a literature review to study the evolution and state of the art of WH systems. The applied methodology identified, presented and discussed past studies concerning hybrid topologies including wind power and hydrogen generation and utilisation systems, from a technical, financial and environmental perspective. Three categories of WH systems were investigated and discussed; grid-connected and autonomous energy storage systems, and configurations used to provide fuel to the transportation sector.

In correspondence to the second, third and fourth task of this PhD project, the second article linked to RQ2 aimed at investigating the wind power sector and electricity market in Denmark and the financial prospects of a hydrogen system participating in the electricity market either as a demand response load or/and a power generating unit. To achieve that, an algorithm of sizing and calculating hydrogen production of the hydrogen system for each examined SC was developed to identify the most financially efficient SC for the investor with the least hydrogen fuel price.

The next article linked to task six and RQ3, comprised the sizing and optimisation of a low-pressure autonomous on-site HRS for light-duty FCEVs in order to meet the hydrogen fuel demand of the city of Herning, Denmark in the case where all bike owners would use FCEBs for their daily commutes. The methodology followed included three main steps consisting of the sizing of the wind turbine based on the wind resource of the region and the estimated hydrogen fuel demand, the sizing of the water electrolysis system and the storage configuration based on the maximum hydrogen production from the wind turbine output, and a financial analysis to estimate the hydrogen fuel cost.

The sixth article documented in this dissertation presented the experimental results of the first phase (see Fig. 2.1) and a comparison analysis of different low pressure refuelling SCs as the first step towards the market development. The methodology followed in this research paper consisted of quantitative analysis of the experimental data and qualitative analysis of the data gathered based on a survey taken by the experiment's participants. The experimental results were compared to the respective results acquired from the application of the algorithm developed in the fourth article to assess the best low-pressure refuelling SC.

Likewise to the sixth article, the next research output presented the results of the second experimental phase and discussed the refuelling processes of the FCEB under different storage pressures. Similarly to the previous paper, a quantitative approach was used to process the data followed by a qualitative analysis of a survey's results regarding the distance the participants were willing to travel and the cost they were willing to pay for refuelling the light vehicle. The most economically favoured SC indicated the type of refuelling infrastructure with the best prospects in the urban light-duty hydrogen mobility market.

The last article investigated the prospects of the light-duty refuelling market from the perspective of a different on-board hydrogen storage of a FCEB for two different regions and compared the results with those acquired from the above-mentioned studies. The methodology included a financial analysis to find the minimum cost of hydrogen where NPV becomes positive for the type of HRS identified to present the most economically appealing case study from both the investor and the consumer perspectives (according to the results of the sixth paper) and an offsite counterpart.

The following sections of the dissertation present the research results as those expressed through the documented articles in respect to the tasks quoted and linked to each of the three RQs.

# 3. What are the socio-economic prospects of light-duty FCEVs' private transportation and its respective infrastructure?

The first RQ has been investigated through two articles following the main methodology as described in the previous section. The aim of these journal articles was on the one hand to identify the state of art of hydrogen technologies in the transportation market and its expected future evolution and on the other to assess the prospects of these technologies from a social perspective.

- D. Apostolou, G. Xydis (2019). A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renewable & Sustainable Energy Reviews*, 113, 109292, https://doi.org/10.1016/ j.rser.2019.109292.

- D. Apostolou, S. N. Welcher (2021). Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark. *International Journal of Hydrogen Energy*, 46(9), pp. 6885-6900. https://doi.org/10.1016/j.ijhydene.2020.11.167

## 3.1 A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects

During the last years, hydrogen based transportation presented a significant growth consisting of the commercialisation of fuel cell electric vehicles and the development on new infrastructure schemes.

This study demonstrates the state-of-the art and the future potential of the emerging hydrogen-based market in road transportation. To this end, a detailed analysis of the current technologies associated with hydrogen refuelling stations including stations' components and categories is presented. Subsequently, future forecasts concerning the development of hydrogen infrastructure along with its corresponding financial evaluation is documented through a thorough literature review. All the referred sources were discussed and compared, concluding to a general outcome showing the prospects of hydrogen in the transportation sector.

Acknowledging the above, this review identified a growing trend in the expansion of hydrogen infrastructure, albeit at this time is still at an initial stage of development, mostly due to the low $H_2$ fuel demand for transportation. However, based on the acquired information and the analysis of the presented data, an increase of the $H_2$ fuel demand in the future will require high investments in the infrastructure sector, which may exceed several billion EUR through the construction of an adequate number of hydrogen refuelling stations. In this regard, the presented studies indicated a number of hydrogen refuelling stations for the next decades based on different scenarios of the future alternative vehicles mix, ranging from several thousands to hundreds of thousands.

Hence, it is concluded that there is a two-way relationship between hydrogen infrastructure and $H_2$ based vehicles. Investments in hydrogen refuelling stations are profitable if the fuel cell vehicles number will grow, and on the other hand, fuel cell vehicles market will be hindered if there is no adequate hydrogen infrastructure development.

### 3.1.1 Introduction

Since the dawn of the 20th century, industrial evolution and rapid economic growth in most western countries induced the need of more energy resources in order to cope with the increasing demand. The vast majority of these resources originated from finite energy sources based on fossil fuels, which comprised the raw material in many sectors of modern society including electric power generation, industrial applications, and transportation. However, this profligate use of fossil fuels resulted on the one hand to major environmental impacts associated mostly to combustion emissions and on the other to an increasing awareness of a future depletion (Day and Day, 2017; Masnadi et al., 2015). Total GHG emissions in 2014 comprised 65% from fossil fuel and industrial processes induced $CO_2$, 11% from land use $CO_2$ emissions, 16% from methane, 6% of nitrous oxide and 2% from fluorinated gases (IPPC and Edenhofer, 2014). The global $CO_2$ emissions from fossil fuels combustion, gas flaring and cement production increased dramatically by 90% especially after the 1970's, reaching in 2014 to more than 36.1 Gt (Fig. 3.1.1), which represented an all-time high (Boden et al., 2017).

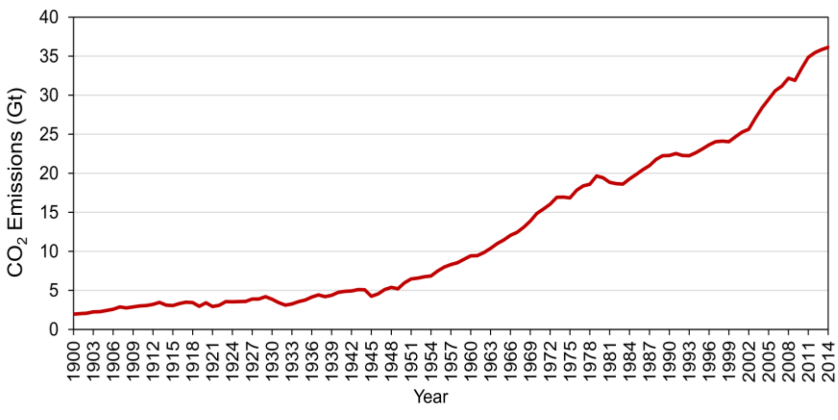



Fig. 3.1.1. Carbon dioxide emissions 1900-2014. Based on (Boden et al., 2017).

One of the main contributors in total emissions from fossil fuel utilization is the transportation sector accounting 24% of global $CO_2$ emissions in 2015, an increase of 68% since 1990 (IEA, 2017a). Specifically, in the EU-28, the transportation sector (excluding civil aviation) was responsible for more than 878 Mt of GHGs $CO_2$-eq. in 2010, while in 2015 this value reached 862 Mt $CO_2$-eq. (European Commission and Eurostat, 2017). Fig. 3.1.2 illustrates the total GHGs and the transportation sector emissions share in EU-28 between 1990 and 2015. Based on the results, although the EU policy for reducing GHG emissions by 20% compared to 1990 levels (European Commission, 2016a) resulted to a gradually reduction of GHG in the last 25 years, the road transportation share increased from around 12% to approximately 20%.

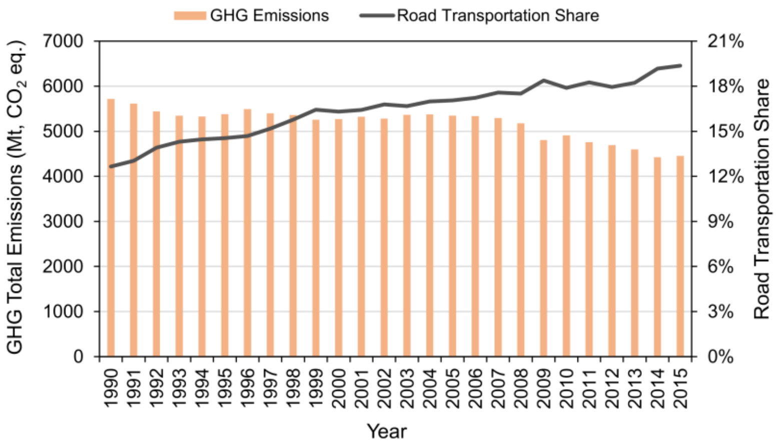



Fig. 3.1.2. EU-28 total GHG emissions and the respective road transportation share 1990-2015. Based on (European Commission and Eurostat, 2017).

In this context, the European policy for reaching a low-carbon economy in 2050 suggests to cut down total GHG emissions to 80% below 1990 levels, which would correspond to approximately 1,143 Mt $CO_2$-eq., a value close to contemporary emissions caused only by transport applications (European Commission, 2016b). Hence, it seems that nowadays, the introduction of new emerging technologies for supporting the transition to environmentally friendlier means of transportation can be considered mandatory. During the last years, “green” mobility technologies are developing constantly with the introduction of new vehicles by the automobile industries and RES based refuelling infrastructures (Bekiaris et al., 2017; Morrison et al., 2018). The most widely accepted and utilised “green” transportation technology is based on BEVs, which use the energy stored in an on-board battery pack to supply an electric motor for the vehicle’s propulsion through auxiliary electronic components (McKinsey & Co, 2010). However, the BEV technologies nowadays present still drawbacks such as limited driving range, long recharging time, deep discharging problems of the battery bank, and high initial investment cost resulting to a scepticism regarding if they can adequately replace conventional vehicles (Serrao et al., 2009; von Helmolt and Eberle, 2007).

One of the most promising alternative options for supporting in parallel to BEVs “green” mobility comprises the introduction of the first commercialised FCEV in 2014 by a major car manufacturing company. Compared to BEVs, FCEVs present several advantages in the sectors where BEVs struggle such as high driving range due to the much higher energy density by weight of hydrogen, very low refuelling time and no battery degradation problems in conjunction to the capability of long term storage of the hydrogen fuel without losses (McKinsey & Co, 2010; Thomas, 2009). Although FCEVs are actually electric vehicles, the energy input to the electric propulsion, stems from hydrogen gas, stored in on-board tanks, which supplies a fuel cell that through electrochemical processes generates electricity (McKinsey & Co, 2010; von Helmolt and Eberle, 2007). In this regard, contemporary light duty FCEVs present similar characteristics with conventional vehicles in terms of utilisation including range autonomy, which may reach 650 km, and low refuelling time that does not overpass 3 min (Brey et al., 2018). Since 2014, when the first FCEV model has been introduced in the market, several automobile companies launched their own mass production FCEVs while others consider developing their models in order to obtain a share in this emerging hydrogen market in the transportation sector. Nevertheless, the establishment of this new technology faces several obstacles that hinder its further expansion and development. The most significant negative factors associated to the feasibility of this venture include the lack of adequate infrastructure and the high cost of ownership (Brey et al., 2018; Michalski et al., 2011).

Based on the above, the main objective of this research is to gather the most relevant studies concerning hydrogen infrastructure development in order to provide an analysis of the current situation of hydrogen technologies in transportation and how these are going to support the transition to “green” mobility in the future. Hence, this study aims to investigate the following RQs:

RQ3.1.1: Which is the current status of hydrogen infrastructure in supporting the FCEVs’ fleet?

RQ3.1.2: What are the prospects of hydrogen technologies towards a low emission transportation in the future?

Hydrogen-based infrastructure in the transportation sector comprises all the important components and facilities associated with the sufficient support of the hydrogen fuel demand of FCEVs. This $H_2$ network includes all the WtW processes of producing and delivering the hydrogen gas to vehicles through HRSs similar to the conventional automobiles. In this context, a hydrogen infrastructure can be defined as a supply chain including production, storage, and transportation and deliverance of hydrogen to final consumers, which in this case are the vehicles’ owners. The above-mentioned stages present a variety of different options concerning their implementation in the supply scheme. Specifically, hydrogen can be produced by utilisation of different mature technologies.

Fig. 3.1.3 shows the basic methods used nowadays for producing hydrogen gas. Up to date, the highest production of hydrogen stems from fossil fuels (i.e. >95%) (Nikolaidis and Poullikkas, 2017). The main methods used in fossil fuel processing to produce $H_2$, are the steam reforming, gasification, pyrolysis, and partial oxidation. All these methods involve catalytic processes, which take place inside specific reactors operating at high temperatures that in some cases may reach 1500 $^oC$ (Guandalini et al., 2016; Nikolaidis and Poullikkas, 2017). On the other hand, the most developed methods for hydrogen production from RES comprise the water electrolysis and the processing of biomass. Water electrolysis is the process of splitting water in hydrogen and oxygen by using electricity to support the reaction, while processing of biomass can be performed either by conventional thermochemical methods (i.e. pyrolysis, gasification) or through biological processes. The latter consists of anaerobic digestion and waste-water treatment through the production of raw biogas, which is then used in a reformer to get hydrogen (Guandalini et al., 2016).

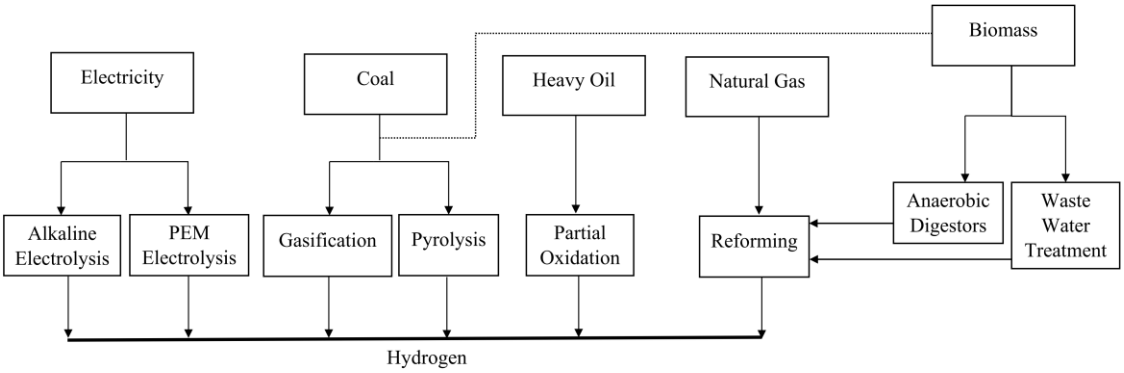



Fig. 3.1.3. Main hydrogen production technologies. Based on (Guandalini et al., 2016; Wietschel et al., 2006).

Currently, more than 100 million metric tons of hydrogen are produced annually (Brown, 2016a), with almost half of this quantity (i.e. 48%) derived from natural gas through steam reforming processes. The lowest share in total production came from water electrolysis (i.e. 2%). The second major source of hydrogen originated from oil through partial oxidation (i.e. 30%), and the third process for producing hydrogen was based on coal through pyrolysis and gasification accounting 18% of total production (IRENA, 2018).

Regarding hydrogen storage processes, $H_2$ can be stored as pressurised gas or as liquid inside proper tanks and via new technologies including metal hydride canisters. Transportation of $H_2$ to retail stations where it is dispensed to customers is accomplished either through road trucks/tankers, tankers by rail or ship, or via dedicated pipelines over long distances (Li et al., 2008). Based on the above, hydrogen infrastructure can be developed under two main topologies. Firstly, similar to conventional fuels, hydrogen can be massively produced at a central site and then distributed to the respective refuelling stations, or it can be generated locally through the use of small-scale $H_2$ production units, resulting to lower fuel transportation requirements. However, both options present advantages and disadvantages associated mainly to cost, reliability, safety and social impacts (Li et al., 2008).

This study aims to analyse the current status and future prospects of HRSs through a literature review in order to provide the necessary information to researchers and stakeholders that focus towards a hydrogen economy in the transportation sector. Moreover, by considering that hydrogen-based vehicles are already commercialised and in contrast, hydrogen infrastructure studies are either outdated or limited in parameters such as investigation of specific locations and different technologies, an overview of the available reports and researches on hydrogen mobility will contribute in acquiring a more detailed and complete perspective on the subject.

### 3.1.2 Methodology

In order to be able to carry out this literature review, the authors followed a specific approach comprising three basic steps (Onwuegbuzie, 2016). Firstly, the collection of the available data on hydrogen infrastructure in the existing literature was of great importance. During this stage, it was essential to find the most relevant articles to the subject in order to discover the exact volume of research done already. Based on the review process, the number of studies concerning the evolution of hydrogen mobility infrastructure was relatively low compared to other technologies in the transportation sector. Specifically, the literature review resulted in approximately 44 papers published since 2000, including journal and conference articles found in different databases including “Scopus”, “Google Scholar” and “Science Direct”, while the reports from international recognised research centres and organisations were estimated to 42.

The contribution of each source to the investigated subject has been determined in order to assess the importance of the findings, locate possible interactions between them, and organise the relevant information. The investigation revealed that studies and reports published a decade ago, tended to be optimistic concerning hydrogen technologies deployment in transportation by 2020. For this reason, publications prior 2005 were excluded from the literature review in order to provide as much accurate and up-to-date data for the current status and future prospects of hydrogen-based mobility.

Additionally, papers presenting identical results from a specific source were also excluded by presenting exclusively the initial research they were based on. The literature review deduced also studies regarding general concepts of hydrogen utilisation for mobility purposes with no specific reference to the status and prospects of the $H_2$ infrastructure and the vehicles’ fleet. For this reason, these studies were not included in the final pool of the presented data. Conclusively, the aggregated data presented in the next sections of this research have been extracted from 21 journal and conference articles, and 35 reports published by research centres and hydrogen-oriented organisations.

At this part, the assessed data concerning hydrogen infrastructure have been used via an iterative process in order to identify and categorise the content of each chapter. In this regard, the retrieved studies were divided to the ones investigating only hydrogen technologies evolution, to others presenting the economic aspects of this evolution, and finally to those that included both the financial and deployment prospects of hydrogen in transportation. Subsequently, the results obtained from the acquired data were compared among each other for creating the general idea of what is the status and the prospects of hydrogen infrastructure in the transportation sector. The third stage of the methodology followed included the presentation of the findings, along with a display of ideas regarding the validity and the common ground of all the analysed information processed during the review. Fig. 3.1.4 depicts the steps followed during the review process.

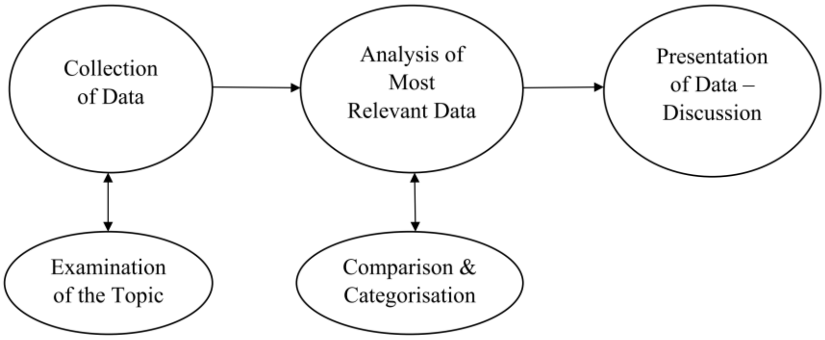



Fig. 3.1.4. Methodology followed during the hydrogen infrastructure review.

In this context, the paper's structure consists of four sections including a description of the $H_2$ retail stations' categories, an analysis of the evolution and the current status of the stations, and a documentation and comparison between different studies concerning future prospects. Finally, the last section includes an examination of the financial issues of hydrogen infrastructure in the transportation sector.

### 3.1.3 Results and discussion

This section of this research presents the retrieved data from the selected sources described in the previous chapter along with a comparative analysis and discussion on the topics. The first main subsection of the results' section consists of definition and categorisation of HRSs in order to comprehend the main components and available types in the hydrogen infrastructure market.

Subsequently, the current status of HRSs and FCEVs are presented and compared to the alternative BEVs' technology schemes. Following, based on the most recent published data, future prospects of hydrogen-based technologies in the transportation sector are quoted.

Beside the evolution of hydrogen infrastructure, the investigation of the investments required to support the aforementioned evolution is of great importance. In this context, the second part of the results and discussion section comprised the presentation of the financial aspects of hydrogen technologies in mobility including current investment cost of infrastructure components, and retail $H_2$ fuel retail prices. Furthermore, forecasts on how these values are expected to evolve based on the expansion of the market have been analysed.

#### 3.1.3.1 Hydrogen refuelling stations

One of the most important components in hydrogen infrastructure for transportation purposes is the HRS. As it was aforementioned, the design of stations can be categorised based on the type of hydrogen production technology used and the fuel generation location, which is either on-site or produced and delivered from a central production unit. Despite the differences arising from the method of producing and delivering hydrogen, the vast majority of retail stations require most of the following components (Alazemi and Andrews, 2015; Qin and Brooker, 2014):

- Hydrogen production unit.
- A purification unit is required in order to secure that hydrogen purity meets the standards for supplying fuel cells (purity above 99.97%) (Ohi et al., 2016).
- Hydrogen compressor for high-pressure storage inside the station's main $H_2$ tanks.
- Hydrogen storage tanks for either compressed gas or liquid $H_2$.
- Hydrogen gas booster, which regulates pressure to 350 bar or 700 bar during the refuelling procedure.
- Cooling unit to reduce hydrogen gas temperature down to -40°C in order to ensure that during fast refills the vehicle's hydrogen tank does not exceed 85°C and ensure safety (de Miguel et al., 2016).
- Safety equipment including pressure relief valves, hydrogen sensors, and waterless fire suppression.
- Mechanical and electrical equipment such as valves, piping, control panels, and high voltage connections.
- Dispensers used to supply the vehicles' $H_2$ high-pressure tanks from the station's compressed storage tanks.

#### 3.1.3.1.1. HRS categories

*3.1.3.1.1.a. Off-site hydrogen production*

The first type of HRSs includes all the stations where hydrogen is delivered from a central production unit through road transport or specific pipelines.

The delivery of hydrogen through road transport is done by heavy-duty trucks where hydrogen is stored in tube trailers as compressed gas (GH2) to pressures of more than 180 bar, or as liquid (LH2) in specialised tanks at cryogenic temperatures of -253$^{o}$C for long distances. However, this latter method of $H_2$ transportation is much more costly than gaseous $H_2$ delivery because of the high amount of energy required to liquefy hydrogen and thus is not currently widely used for supplying HRSs (Qin and Brooker, 2014).

On the other hand, gaseous hydrogen is initially produced in large industrial facilities at relatively low pressures of up to 30 bar, and then is compressed to approximately 180 bar to 200 bar for truck delivery or up to 70 bar for pipeline transportation (Gillete and Kolpa, 2007).

Pipeline $H_2$ transportation is considered a low cost solution in the case of an existing pipeline network such as the one located in USA reaching approximately 2,600 km; otherwise, the high initial cost of new pipelines' construction consists of a major barrier for a network's expansion. This is associated to the inherent properties of hydrogen concerning its molecule characteristics, which mandates the use of certified equipment and materials (US Department of Energy, 2018a).

Acknowledging the above, this type of HRS does not require the first two components mentioned in the previous subsection, but instead it is necessary to include a receiving port able to support proper connectivity with the respective method of $H_2$ deliverance (Alazemi and Andrews, 2015). Fig. 3.1.5 presents the main components comprising the HRS with off-site compressed gas hydrogen production.

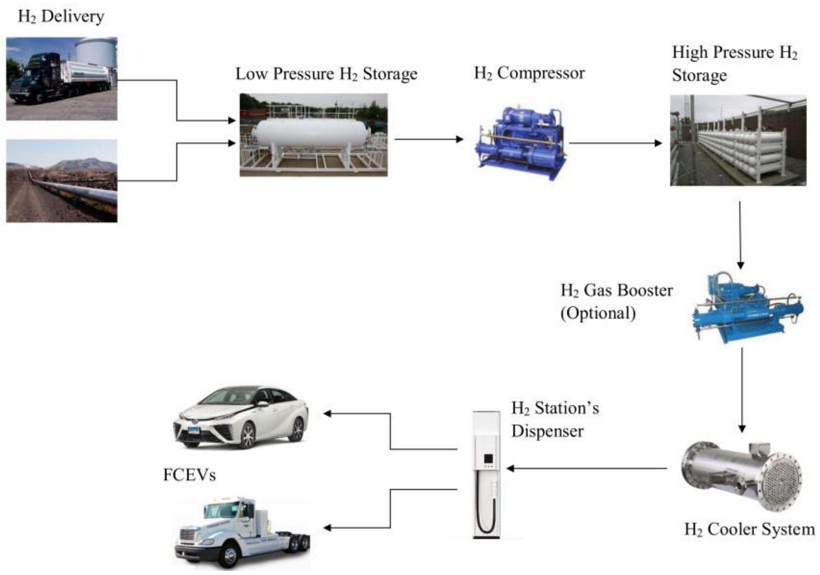



Fig. 3.1.5. Off-site $H_2$ production hydrogen gas refuelling station's main components.

*3.1.3.1.1.b. On-site hydrogen production*

The second type of HRSs is similar to the first one in terms of operational stages, but the hydrogen used to refuel the FCEVs is generated locally. The two most frequently used technologies for on-site hydrogen production comprise the SMR and the water electrolysis. Compared to the off-site HRSs, on-site configurations present technical capacity limitations, which depends on the output quantity of the $H_2$ generators, with a typical range between 100 kg/day to 1000 kg/day (Qin and Brooker, 2014). However, current operating on-site HRSs do not present daily $H_2$ production capacities above 400 kg, with the most predominant systems being in the order of 100 kg$H_2$/day (H2Tools, 2018).

The SMR consists of a number of reactors, where fuels such as natural gas or biogas, in presence of a catalyst react with steam under pressures up to 25 bar and produce $H_2$ and CO. The process also includes a water-gas shift reaction where the produced CO reacts with water vapour to form $CO_2$ and hydrogen. Hence, for the SMR unit operation, water and a heat sources are required (US Department of Energy, 2018b).

Water electrolysis on the other hand, is the process where water splits to hydrogen and oxygen with the application of direct current electric voltage. The technologies that are mostly used in HRSs are the alkaline and the PEM electrolysis (Kavadias et al., 2018). Apart from a sufficient electric power input, both applications require a deionised water input along with a cooling system for preventing the operational temperature of electrolysis to reach values above 100$^{o}$C. Alkaline electrolysers operate at approximately in the range of 65$^{o}$C and 100$^{o}$C for safety reasons, while commercialised PEM electrolysers operational temperature does not exceed 100°C in order to protect the Nafion membrane from dehydration that results to lower proton conductivity (Bessarabov et al., 2016). However, research on PEM systems indicates that operation under temperatures of 130°C through the utilisation of enhanced membranes contributes to higher cell current density and therefore hydrogen production rates increase (Toghyani et al., 2018).

The produced hydrogen from both technologies (i.e. methane reformer, water electrolysis) may include impurities, which should be removed from the gas stream prior the refuelling processes due to technical constraints of the FCEVs' operation. To this end, it is mandatory to introduce a hydrogen purification system. Additionally, the produced hydrogen exits the generator units at relatively low pressures and thus a buffer storage tank is required before storing the hydrogen at higher pressures (Nistor et al., 2016). Thus, it is apparent that although delivery of hydrogen is not required in on-site production HRSs, this type of stations includes more processes arising from the introduction of additional technologies for hydrogen production. Fig. 3.1.6 depicts the main components of an on-site HRS.

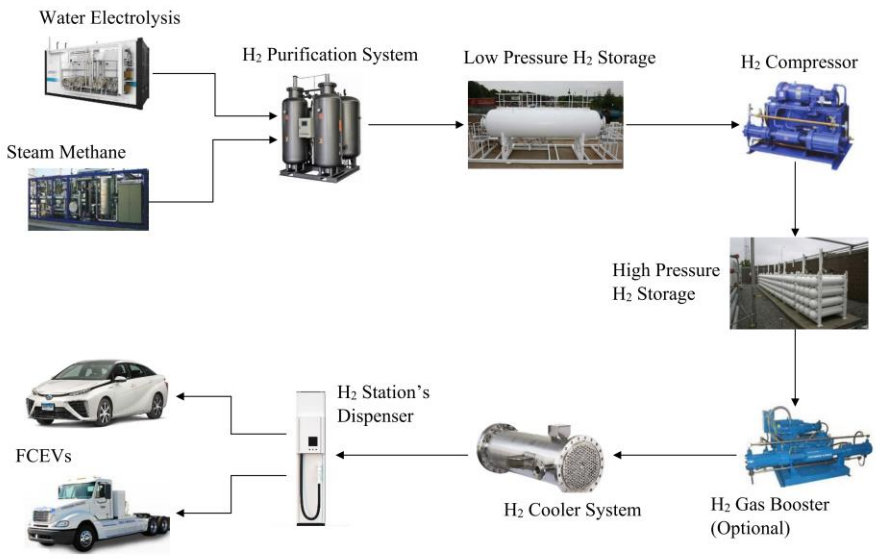



Fig. 3.1.6. On-site $H_2$ production hydrogen gas refuelling station's main components.

*3.1.3.1.1.c. Comparison between the two HRSs types*

The inherent differences between the two main types of HRSs stem from the hydrogen source used for providing the fuel during the refuelling processes. Concerning the HRS's hydrogen storage topology, the off-site stations are simpler and apart from the relative infrastructure for receiving the delivered hydrogen, the system is more oriented towards the compression-refuelling processes. In this regard, off-site HRSs' capacity can vary and depending on the storage facilities, it can be sized based on the demand. Most of the stations nowadays present capacities in the range of 100 $kgH_2$/day to 520 $kgH_2$/day for compressed GH2, while for LH2 storage this capacity increases to more than 1000 $kgH_2$/day (H2Tools, 2018).

On the other hand, on-site hydrogen production refuelling stations include the equipment for producing and handling the $H_2$ gas prior its initial storage. The main equipment used comprises a hydrogen generator (either a methane steam reformer or a water electrolysis unit) along with a purification system in order to increase the purity of hydrogen fuel to acceptable values (i.e. fuel index above 99.97%) in compliance with the ISO regulations (Ohi et al., 2016). Most of the current on-site HRSs present a capacity between 100 $kgH_2$/day and 400 $kgH_2$/day (H2Tools, 2018), while plans to increase the capacity to up to 8,000 $kgH_2$/day are considered for future HRSs for fuel cell trucks (O'Dell, 2019a).

From a financial perspective, on-site hydrogen production stations exhibit a significantly higher capital cost due to the extra hydrogen production components. Especially, for HRSs with on-site water electrolysis $H_2$ production, the investment may reach more than 1.5 times higher capital cost than a same capacity off-site station. In this context, the levelised hydrogen fuel cost for on-site stations is currently higher reaching in some cases twice the cost found in the off-site counterparts (McKinney et al., 2015).

#### 3.1.3.1.2. Current status

Since the 1970s, many automobile industries focussed in developing new non-fossil fuel based propulsion technologies such as fuel cells powered motors due to the increasing environmental awareness and the oil crisis occurred in 1973. These prototype vehicles however were limited only to one-off demonstration purposes (Fuel Cell Today, 2018). It was not until 1994 when the first experimental production of a passenger FCEV (the '*NeCar I*') was introduced by Daimler-Benz (Panik, 1998). During the last 20 years, most of the automotive industries developed FCEV models aiming to keep up with the transition to environmentally friendlier ways of transportation but none of these models entered actually the market. To this end, this development of prototypes did not require an extensive network of hydrogen stations but only facilities able to support the experimental phases of each project. However, apart from the deployment of these pilot FCEVs, hydrogen powered fuel cells have been extensively used in material handling vehicles such as forklifts for many years. For instance, more than 15,000 and 7,000 FC material handling vehicles are in operation globally and in USA respectively today, suggesting the need of an adequate HRSs' number (Fuel Cell & Hydrogen Energy Association, 2018).

As already mentioned, the first commercialised FCEV was introduced in 2014 followed by four other automotive industries with three more commercialised vehicles, and one in the pre-production phase (Daimler, 2018a; Fuel Cell & Hydrogen Energy Association, 2018; IEA, 2019a). At this time, the number of FCEVs reaches 12,900 with more than 4,500 units sold only in 2018, suggesting an increasing trend during the last three years (IEA, 2019a, 2019b). In this context, the support to a continuous increasing number of fuel cell vehicles necessitates the introduction of a more complex HRSs' network.

Regarding the global number of HRSs, more than 375 stations are in operation today compared to 320 in 2017 with the majority being publicly accessible (IEA, 2019a; Ludwig-Bölkow-Systemtechnik, 2017; SÜD, 2017; US Department of Energy, 2018c; Wasserstoff-Tankstellen weltweit, 2019). At the end of 2018, the region with the most HRSs in operation was Europe with more than 170 HRSs, while second ranked Asia (most of them in Japan) with approximately 130 HRSs, and third America (mostly in USA) with more than 70 stations installed (IEA, 2019a; SÜD, 2017; US Department of Energy, 2018c). Fig. 3.1.7 indicates the number of HRSs by country at the end of 2018.

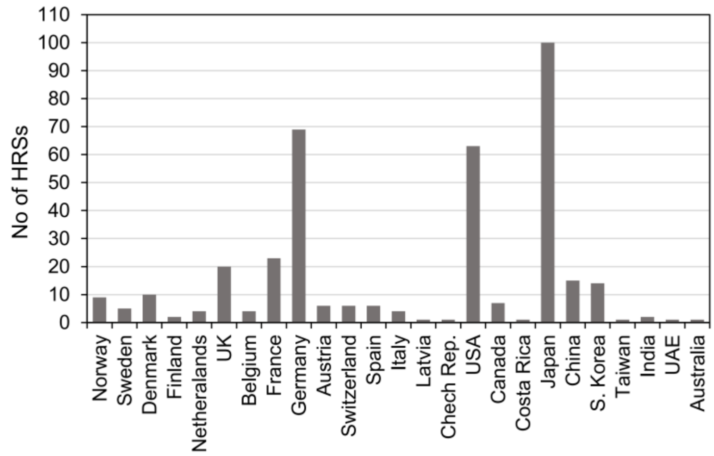



Fig. 3.1.7. Global HRSs in end 2018. Based on (IEA, 2019a).

On the other hand, although Europe compared to other regions presents a more developed hydrogen network in terms of HRSs, the leader in FCEVs number is North America with more than 45% of total vehicles, followed by Asia with 43%, and last Europe with approximately 11% share in the FCEVs fleet (IEA, 2019a).

The European hydrogen market in the transportation sector is relatively new, where the first light duty FCEVs have been introduced (for leasing only) in 2013. Compared to other alternative propulsion systems such as the BEVs that entered the vehicle market earlier, FCEVs present a similar increasing trend, although their number are still very low. At the end of 2017, total FCEVs in Europe numbered 799 vehicles from which 602 were passenger cars and 197 light duty commercial vehicles, while total BEVs reached 447,150 vehicles (EAFO, 2019a; European Automobile Manufacturers Association, 2018). At the end of 2018, the number of FCEVs in Europe increased to approximately 1,110, which corresponds to almost 40% of increase compared to the 2017's number (EAFO, 2019a). Figs 3.1.8 and

3.1.9 present the evolution of BEVs and FCEVs (including passenger and commercial vehicles) respectively in Europe by country since 2010.

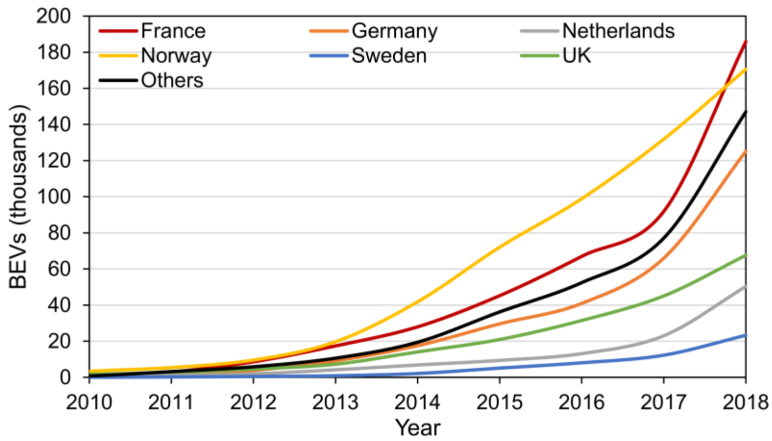



Fig. 3.1.8. BEVs evolution in Europe since 2010. Based on (EAFO, 2019b; European Automobile Manufacturers Association, 2018; IEA, 2017b).

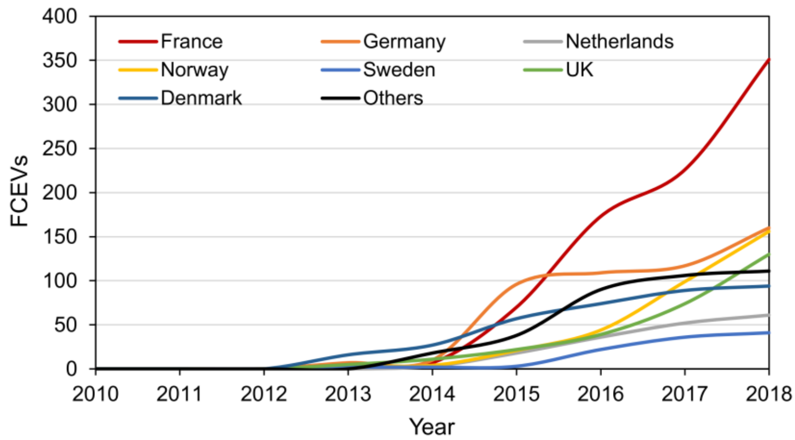



Fig. 3.1.9. FCEVs evolution in Europe since 2010. Based on (EAFO, 2019c).

Based on the above figures, both vehicles present an increasing trend in all countries, but one may observe the high increase of the FCEVs numbers occurred after 2014, when the first commercial FCEV has been introduced in the market. Similarly, the number of HRSs in Europe presented an increasing trend during the last years, in order to support the increasing trend in passenger FCEVs but also to provide hydrogen to private company fleets and other leased vehicles. Fig. 3.1.10 indicates the evolution of charging stations in Europe and the number of BEVs per station since 2011. Similarly, Fig. 3.1.11 illustrates the respective diagram for FCEVs – HRSs for the period 2011 – 2017.

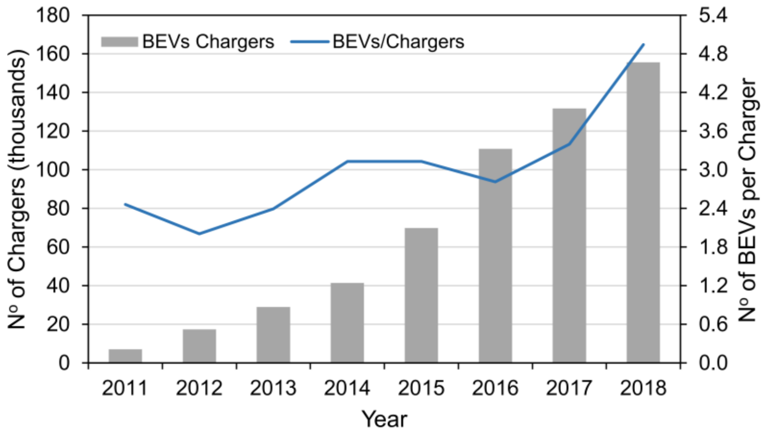



Fig. 3.1.10. BEV chargers and number of BEVs/charger evolution in Europe since 2011. Based on (EAFO, 2019d; IEA, 2017b).

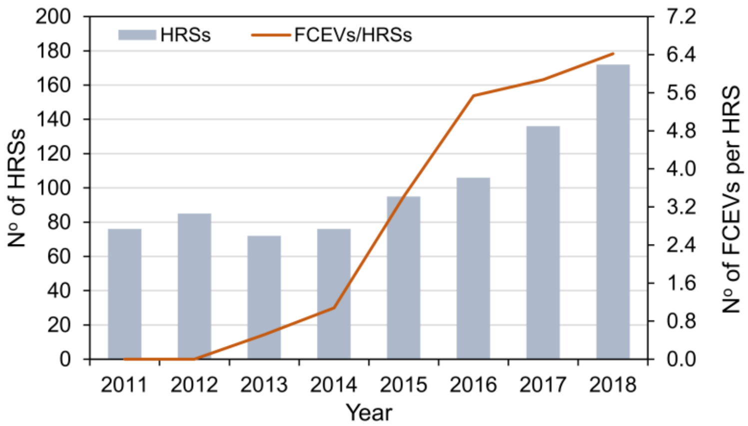



Fig. 3.1.11. HRSs and number of FCEVs/HRS evolution in Europe since 2011. Based on (EAFO, 2019c; Ludwig-Bölkow-Systemtechnik, 2017).

These diagrams (i.e. Figs 3.1.10, 3.1.11) show the relationship between the respective investigated vehicles and the infrastructure schemes for each one of those during the last years in Europe. As the results indicate, the number of HRSs used mostly to support company fleets of material handling vehicles and other pilot projects remained almost constant until 2014, when it presented an increasing trend due to the increased demand after the commercialisation of the first FCEVs. In terms of vehicles served per HRSs and BEVs chargers, it is apparent that the network of BEVs charging stations in Europe is developed simultaneously with the continuously increasing number of BEVs (see Fig. 3.1.8) and between 2011 and 2016, there was no substantial deviation of the number of cars supported by each charger. However, since 2017, it seems that the number of vehicles increases at a higher pace than this of the relevant infrastructure resulting to more BEVs per charger in 2018. On the other hand, the introduction of passenger FCEVs in the European market since 2014 required a more extended network of HRSs. To this end, more HRSs have been deployed and as it was aforementioned, Europe at the end of 2018 ranked first amongst all regions globally in the total number of stations. However, Fig. 3.1.11 dictates that the number of FCEVs per HRS increased significantly during the last three years indicating that in the near future it will be mandatory to implement new HRSs in order to support the expansion of the FCEVs' market.

#### 3.1.3.1.3. Future prospects

Most of the studies including the future evolution of HRSs' number and capacity indicate an exponential increase, which will arise from the demand of $H_2$ to supply a growing fleet of FCEVs. The basic topology behind this theory is based on forecasts concerning the evolution of conventional vehicles with the introduction of FCEVs as a share in total vehicles' fleet number (Iordache et al., 2017). In this regard, a significant number of reports focus only on presenting scenarios relative to the penetration of the FCEVs in the transportation market. In this case, for being able to categorise these studies based on the required number of hydrogen stations' facilities for supporting the FCEVs' fleet future projections, one may take into account the following parameters.

According to Robinius et al. (2018), the number of fuel cell vehicles that can be served from a medium sized HRS (420 $kgH_2$/day) in a daily basis reaches 75 cars (Robinius et al., 2018), while an indicative autonomous range of contemporary FCEVs is approximately 550 km (Gurz et al., 2017) and is expected to increase up to 1000 km by 2030 (Hydrogen Council, 2017a). The average annual travelled distance of passenger vehicles is 15,000 km (Smit et al., 2007). Based on the data above, and by using Eqs. 3.1.1 and 3.1.2, the minimum number of HRSs to support a FCEVs passenger fleet can be estimated.

$$Days\ \ to\ \ refuel = \frac{Autonomous\ \ range}{km\ \ per\ \ day} \tag{3.1.1}$$

$$No\ \ of\ \ \ HRSs = \frac{No\ \ of\ \ FCEVs\ \ fleet/Days\ \ to\ \ refuel}{Max\ \ No\ \ of\ \ FCEVs\ \ per\ \ HRS} \tag{3.1.2}$$

The IEA, estimated by a rollout scenario of FCEVs deployment including USA, EU 4 countries (Germany, France, UK, Italy), and Japan that the number of hydrogen based vehicles will reach 30,000 in 2020, 8 million in 2030, and 125 million in 2050. To this end, a feasible number of HRSs for supporting the FCEVs' fleet in 2020, 2030, and 2050 has been estimated to above 680, 16,000, and 57,000 refuelling spots respectively in all global regions (IEA, 2015). Additionally, within the framework of Hydrogen Implementing Agreement (HIA), four countries (i.e. Germany, UK, Japan, and S. Korea) enacted measures to support the growing trend towards the establishment of hydrogen mobility as a supplementary solution to BEVs in 'green' transportation. According to official data, Germany plans to implement up to 400 HRSs by 2023, UK 65 by 2020, Japan 1000 stations by 2025, and S. Korea 21 HRSs until 2020 and 211 by 2025. The hydrogen stations in Japan and S. Korea in 2025 should be able to support a forecasted fleet of 2 million and 10,000 vehicles respectively (Weeda and Elgowainy, 2015). In this context, Tanç et al. (2019) studied the vision of hydrogen mobility for the next decades and presented their results in relation to the number of HRSs and FCEVs fleet. The main markets identified as USA, Japan, and EU were examined showing a number of future HRSs in 2035 of 3,810 stations and 25,600 for USA and EU in 2050 (Tanç et al., 2019). It is estimated that in 2050 only in California at least 10,000 HRSs would be operative, while the assumption used for the number of the anticipated FCEVs in 2040 was based on Morrison et al. (2018) who presented projected numbers of FCEVs between 2020 and 2040 in USA (Morrison et al., 2018). The latter authors by using as a baseline ramp up rate comparable to the growth of hybrid and BEVs, they concluded that a scenario for FCEVs number could be 23,000 for 2020, 78,000 for 2025, 3,300,000 for 2030 and 28,000,000 for 2040 (Morrison et al., 2018; Tanç et al., 2019).

Similar studies have been also published by other institutes and private companies including among others 'Shell GmbH'/'Wuppertal Institute', 'Hydrogen Council', and NREL / CEMAC. Shell GmbH in collaboration with Wuppertal Institute presented through a 2017 report, estimations on how FCEVs fleet will evolve by 2050 for USA, EU 4, and Japan. Based on their published report, FCEVs number will show an increasing trend, with 12 million FCEVs in 2030, 58 million in 2040, and 115 million vehicles in 2050 (Adolf et al., 2017). By using Eqs. 3.1.1 and 3.1.2, these fleet numbers correspond to minimum 1,680 for 2030, 8,100 for 2040, and 16,000 HRSs for 2050 based on today's specifications of FCEVs and HRSs in terms of driving range and capacity respectively.

On the other hand, the 'Hydrogen Council' forecasts - a rather optimistic scenario compared to other studies -that the hydrogen demand will reach 22 EJ due to the high share (i.e. 35%) of hydrogen 'mobility' in transportation by 2050. Its estimations suggest a fleet of 15 million passenger FC cars and 500,000 hydrogen fuelled buses and trucks by 2030, while for 2050 these numbers are increasing to 400 million and 20-25 million respectively (Hydrogen Council, 2017a). This can be translated to a minimum number of at least 15,000 HRSs by 2030 and 59,400 HRSs by 2050. Current announcements for HRSs declare the development of 1100 stations by 2020, 2,800 by 2025 to support a fleet of two million vehicles, and more than 5,000 HRSs by 2030, suggesting the feasibility of deploying the aforementioned number of FCEVs by 2030 (Hydrogen Council, 2017a, 2017b).

In the context of future forecasts concerning FCEVs and HRSs deployment, NREL in collaboration with CEMAC, presented in the 'Fuel Cell Seminar and Energy Expo 2015' in Los Angeles, USA, estimations on the future evolution of FCEVs fleets and HRSs. Based on the presentation, the 2020 estimations suggest more than 30,000 FCEVs and 990 HRSs globally, while for the 2030 the number of FCEVs and HRSs is expected to exceed 250,000 and 3,300 respectively (Mayyas, 2015).

According to the previous sections of this paper, one of the regions presenting high development in FCEVs' fleet and hydrogen infrastructure is the west coast of USA and specifically the California State. The 'International Council on Clean Transportation (ICCT)', in October of 2017 published a briefing report on hydrogen fuelling infrastructure indicating that the FCEV's fleet in California will increase to more than 60,000 cars in 2025, while the HRSs' number will reach 120 refuelling spots (Isenstadt and Lutsey, 2017). Additionally, a detailed analysis on the prospects of hydrogen-based transportation has been held by NREL suggesting the growth of FCEVs and HRSs by 2030 in California. Based on the results, the number of HRSs will reach 100 by 2020 and 440 by 2030, while the corresponding FCEVs on the roads by 2030 will reach one million vehicles (Melaina and Penev, 2013). A report published by the 'California Energy Commission' in 2015 presented three scenarios concerning the evolution of the number of HRSs for the years 2020 to 2025. The scenarios consist of an 'expected', a 'delayed' and a 'robust' option. It is argued that the projected number of FCEVs in 2021 would reach 34,300 vehicles while the corresponding number of HRSs is projected to 69, 168 and 177 in the 'delayed' (dsc), the 'expected' (exsc) and the 'robust' (robsc) scenarios respectively. However, the evolution of the number of stations is different for each scenario showing an increase to 109 HRSs in 2025 for the 'delayed' option, 813 HRSs for the 'expected' option, and 1,739 HRSs for the 'robust' option (McKinney et al., 2015).

Iordache et al. (2017) analysed through their research the rollout of HRSs infrastructure and passenger FCEVs in Europe by country. In their study, the development scenarios (sc) of HRSs and the FCEVs' fleet were based on an assumed future share of the hydrogen stations and FCEVs by using as a reference case the number of petrol stations and total vehicles in 2015. The acquired results for FCEVs in Europe showed scenarios of 11.6 million (SC3.1), 23.2 million (SC3.2), and 34.8 million (SC3.3) cars in 2030, while for the HRSs indicated an approximate number of 2,400 (SC3.1), 6,000 (SC3.2), and 9,000 (SC3.3) hydrogen stations by 2030 (Iordache et al., 2017).

In this context, 'Mc Kinsey' consultancy in collaboration with other private companies in the hydrogen sector and governmental institutions such as the fuel cell & hydrogen joint undertaking published a report on prospects of 'green' mobility in Europe. According to the data presented, the balanced scenario indicates a 25% penetration of FCEVs in the 2050s' vehicle market reaching approximately 65 million cars. On the other hand, the expansion of the HRSs' network will evolve from 755 stations in 2020 to 5,100 in 2030 and 18,200 in 2050 (McKinsey & Co, 2010).

The prospects of hydrogen mobility in Europe have also been presented in a roadmap report published in 2019 by the fuel cell & hydrogen joint undertaking. The report included a forecast on the required HRSs to cover the demand of the emerging FCEVs market. The number of vehicles projected for 2050 was estimated based on a no-consolidated (ncsc) and an ambitious (ambsc) scenario resulting to 2.5 million and 53.4 million FCEVs respectively. The corresponding HRSs number to support this growing fleet of hydrogen vehicles is estimated to 1,500 stations by 2025, 3,700 by 2030, 8,500 by 2035, and 15,000 by 2040 (FCH 2JU, 2019).

The two European countries with the largest passenger vehicles' fleet at this time comprise Germany and Italy with more than 45 million and 37 million cars respectively (Iordache et al., 2017). Köhler et al. (2010) presented their results concerning the transition to hydrogen transportation in Germany. The lead scenario under investigation indicates that the number of FCEVs will increase to 400,000 in 2030, and will reach 17,000,000 in 2040, 37% of today's Germany's car fleet. On the other hand, the number of HRSs based on this scenario, will reach 4,000 stations by 2030, and will exceed 14,000 by 2040 (Köhler et al., 2010). Another recent paper by Emonts et al. (2019), examined different scenarios for 2050 regarding the introduction of hydrogen technologies in road transportation in Germany. The authors estimated that number of FCEVs would range between 460,000 and 32,870,000, while the respective scenarios for HRSs' number would be between 420 and 10,747 (Emonts et al., 2019).

Similarly, another study focussing on the prospects of hydrogen-based transportation has been published by Viesi et al. (2017), who investigated a scenario for the implementation of hydrogen mobility in Italy. The authors distinguished the results into two categories for both HRSs and FCEVs. One concerning passenger vehicles and another for hydrogen fuelled buses. According to their results, hydrogen is going to be exploited significantly in the transportation sector mainly after 2025. Specifically, the Italian FCEVs' fleet is expected to comprise 293,700 cars and buses by 2030, 1.61 million vehicles by 2040, and 8.52 million by 2050. The respective HRSs growth will encounter more than 440 stations in 2030, approximately 3,200 stations in 2040, and will reach 6,000 stations by 2050 (Viesi et al., 2017).

According to Figs. 3.1.8 and 3.1.9, one of the leaders in the European BEV and FCEV market is Norway. The transportation sector in Norway should decrease emissions by 75% from 2005 to 2050 in order to support the set by the government GHG emissions reduction targets. To this end, it is expected that BEVs and FCEVs will contribute significantly to this venture. Forecasts show that by 2020 Norway will have more than 45 HRSs installed able to serve up to 22,500 FCEVs, and by 2050 these numbers will increase up to 1,100 and 1.7 million respectively (Stiller et al., 2010).

According to Fig. 3.1.7, the most developed hydrogen market and particularly hydrogen infrastructure until now is in Japan. ‘Hydrogen Energy Navi’ is an online platform supporting research and development of hydrogen utilisation in Japan and provides information regarding hydrogen transportation in this specific country. In this context, Japan aims to reach a goal of 160 HRSs by 2020, 320 HRSs by 2025, and 900 by 2030 in order to support a growing fleet of FCEVs that are projected to reach 40,000 by 2020, 200,000 by 2025, and 800,000 by 2030 (Hydrogen Energy Navi, 2019).

Xu et al. (2017) published a research on the strategy of introducing a hydrogen transportation market in Shenzhen in China. The authors by taking into consideration that the Shenzhen government have put restrictions to the new vehicle registrations along with the share of FCEVs in the annual new registrations, they concluded to three possible scenarios. The ‘cautious’ (csc) scenario indicated a number of 1,028 and 9,432 FCEVs by 2020 and 2025 respectively, while the ‘moderate’ (msc) scenario showed that in 2020 and 2025 there will be 4,090 and 17,360 FCEVs. On the other hand, the ‘optimistic’ (opsc) scenario projected the number of FCEVs to 7,028 for 2020 and 42,640 for 2025. The respective HRSs for 2020 are projected to be 10 (three medium and seven small) in order to cover the hydrogen fuel demand (Xu et al., 2017).

In this context, China’s targets on hydrogen technologies in the transportation sector have been addressed by the “Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Vehicles”. According to the given data, China aims to reach 100 HRSs by 2020 to support a fleet of 5,000 FCEVs, while for 2025 and 2030 these number are projected to 300 HRSs, 50,000 FCEVs, and 1000 HRSs and 1,000,000 vehicles respectively (SAE, 2016).

The next table (Table 3.1.1) summarises the basic scenarios concerning the expansion of refuelling stations and FCEVs towards a sustainable transportation.

Table 3.1.1. Recent studies for the HRSs and FCEVs future evolution.

| Source | Year | Region/Country | No of FCEVs (thousands) | No of HRSs |
|---|---|---|---|---|
| (IEA, 2015) | 2020 | USA | 30 | 680 |
| | 2030 | EU 4 | 8,000 | 16,000 |
| | 2050 | Japan | 125,000 | 57,000 |
| (Weeda and Elgowainy, 2015) | 2020 | UK | | 65 |
| | 2020 | S. Korea | | 21 |
| | 2023 | Germany | | 400 |
| | 2025 | S. Korea | | 211 |
| | 2025 | Japan | | 1,000 |
| (Adolf et al., 2017) | 2030 | USA, EU 4, Japan | 12,000 | 6,667[1] |
| | 2040 | | 58,000 | 32,222[1] |
| | 2050 | | 115,000 | 63,888[1] |

| Source | Year | Region/Country | No of FCEVs (thousands) | No of HRSs |
|---|---|---|---|---|
| (Tanç et al., 2019) | 2035 | EU, USA, Japan | | 3,810 |
| | 2050 | EU, USA | | 25,600 |
| (Morrison et al., 2018) | 2020 | USA | 23 | 23[1] |
| | 2025 | | 78 | 80[1] |
| | 2030 | | 3,300 | 1,833[1] |
| | 2040 | | 28,000 | 15,555[1] |
| (Hydrogen Council, 2017a) | 2030 | Globally | 15,000 | 15,000 |
| | 2050 | | 425,000 | 236,111[1] |
| (Mayyas, 2015) | 2020 | Globally | > 30 | 990 |
| | 2050 | | > 250 | > 3,300 |
| (Isenstadt and Lutsey, 2017) | 2025 | California (USA) | 60 | 120 |
| (Melaina and Penev, 2013) | 2020 | California (USA) | | 100 |
| | 2030 | | 1,000 | 440 |
| (McKinney et al., 2015) | 2021 | California (USA) | 34.3 | 69 (dsc) |
| | | | | 168 (exsc) |
| | | | | 177 (robsc) |
| | 2025 | | | 109 (dsc) |
| | | | | 813 (exsc) |
| | | | | 1,739 (robsc) |
| (Hydrogen Energy Navi, 2019) | 2020 | Japan | 40 | 160 |
| | 2025 | | 200 | 320 |
| | 2030 | | 800 | 900 |
| (Iordache et al., 2017) | 2030 | Europe | 11,608 (SC3.1) | 2,400 (SC3.1) |
| | | | 23,215 (SC3.2) | 6,000 (SC3.2) |
| | | | 34,823 (SC3.3) | 9,000 (SC3.3) |
| (McKinsey & Co, 2010) | 2020 | Europe | | 755 |
| | 2030 | | | 5,100 |
| | 2050 | | 65,000 | 18,200 |
| (FCH 2JU, 2019) | 2025 | Europe | | 1,500 |
| | 2030 | | | 3,700 |
| | 2035 | | | 8,500 |
| | 2040 | | | 15,000 |
| | 2050 | | 2,500 (ncsc) | 2,564[1] |
| | | | 53,400 (ambsc) | 29,666[1] |
| (Köhler et al., 2010) | 2030 | Germany | 400 | 4,000 |
| | 2040 | | 17,000 | 14,000 |
| (Emonts et al., 2019) | 2050 | Germany | 460 – 32,870 | 420 – 10,747 |
| (Viesi et al., 2017) | 2030 | Italy | 293 | 440 |
| | 2040 | | 1,610 | 3,200 |
| | 2050 | | 8,520 | 6,000 |
| (Stiller et al., 2010) | 2020 | Norway | 22.5 | 45 |
| | 2050 | | 1,700 | 1,100 |
| (SAE, 2016) | 2020 | China | 5 | 100 |
| | 2025 | | 50 | 300 |
| | 2030 | | 1000 | 1000 |

| Source | Year | Region/Country | No of FCEVs (thousands) | No of HRSs |
|---|---|---|---|---|
| (Xu et al., 2017) | 2020 | Shenzhen (China) | 1 | 10 |
| | | | 4 | |
| | | | 7 | |
| | 2025 | | 9.4 | |
| | | | 17.3 | |
| | | | 42.6 | |

[1] Based on authors' estimations (Eqs. 3.1.1, 3.1.2)

*3.1.3.1.3.a. Discussion on the forecasted evolution of HRSs*

As it becomes evident from the above indicative review of the literature, some studies present similar results especially in short term forecasts, while others show large deviations. This is happening on one hand due to the different perspectives the authors use during their research (optimistic/pessimistic scenarios), and on the other because of the period each research was compiled. Reports that were published at the first half of this decade indicate a rather optimistic view of hydrogen evolution in transportation. However, after the commercialisation of the first FCEVs, the market share of both HRSs and FCEVs in the transportation sector seems to be hindered by several factors comprising mostly the high cost of investment.

The next figure (Fig. 3.1.12) indicates the trend in the global evolution of HRSs based on the previously described results from journal articles and scientific reports. Studies that provide data on specific regions (i.e. California, Europe) have been also included but modified to global estimated values based on the assumption that the current share of HRSs in these regions will be similar to the share in future global stations.

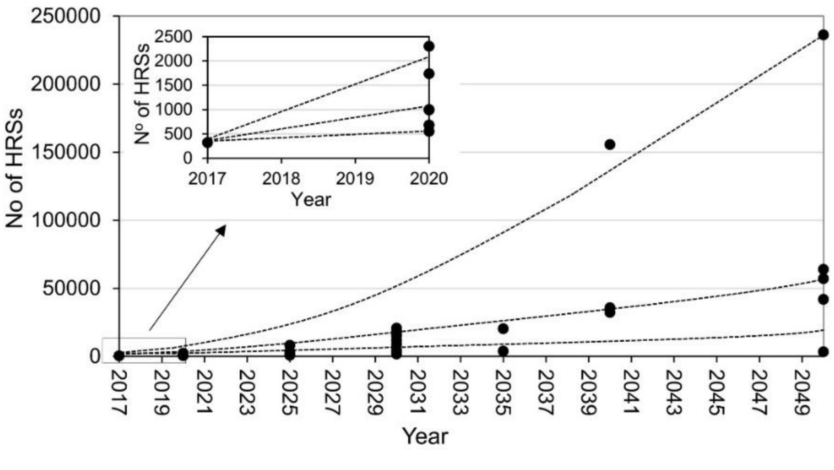



Fig. 3.1.12. Future evolution of HRSs based on different forecasts. Based on Table 3.1.1.

According to Fig. 3.1.12, one can distinguish three main increasing trends concerning the number of HRSs, which in two of the three cases is expected to increase significantly by 2030 and this growth seems to accelerate even more between 2030 and 2050. The three trend lines indicate that there are three possible scenarios showing the evolution of the number of HRSs based on the penetration of FCEVs in the transportation market. All studies show that there will be an increase in the number of HRSs although the increasing rate will vary depending on the demand. Most studies indicate a number of approximately 25,000 HRSs by 2030 and 50,000 stations by 2050. One can also observe that there are cases, where some forecasts present significant deviations (i.e. for 2040, 2050) compared to the majority of other studies' results. By taking into account the majority of the forecasted values, it is more likely that the deviated values in reality will converge closer to the derived trend lines in order to be in accordance to the majority of studies.

#### 3.1.3.2 Financial aspects

Currently, the major parameter limiting the development of the hydrogen market in the transportation sector comprises the high investment cost of both infrastructure and vehicles' fleet. To this end, most of the studies published during the last years focus on the presentation of future forecasts in correlation with the cost evolution of $H_2$-based technologies in transportation. The vast majority of these studies indicate that the investment cost of HRSs and FCEVs, along with the $H_2$ fuel retail price are going to be reduced in the years to come following the transition to economies of scale in the hydrogen sector and the expansion of the market.

##### 3.1.3.2.1. Cost of hydrogen infrastructure development

According to IEA, the current investment cost of a HRS ranges between €1.2 and €2 million and is expected to drop to approximately €0.8 to €2.1 million by 2020 and €0.6 to €1.6 million by 2023, if the FCEVs' market increase to a degree where $H_2$ demand for refuelling would grow significantly. For the distribution of hydrogen fuel to HRSs, (offsite $H_2$ production) tube trailer trucks with capacity of 300 kg of $H_2$ and pipelines are used extensively nowadays. The cost of compressed gaseous hydrogen delivery is approximately €800 times the capacity of the $H_2$ stored mass quantity. On the other hand, although pipelines are considered a low-cost $H_2$ delivery option, the initial investment is very high ranging between €400 thousands and €3.2 million per km. In terms of FCEVs cost, IEA's report suggest that compared to other 'green' vehicles, this will be at the same range. A contemporary FCEVs in the USA costs approximately €48.5 thousands and this cost is expected to reduce to €27.2 thousands by 2030, and €27 thousands by 2050 (IEA, 2015; Weeda and Elgowainy, 2015).

Adolf et al. (2017) compiled a report on behalf of “Shell GmbH” concerning hydrogen technologies. The study presents the current cost of HRSs in California ranging from €0.8 to €8.0 million with the majority of stations’ cost between €1.6 and €2.4 million. These values are highly depending on the daily dispensing capacity and the type of the HRSs. For small HRSs with on-site $H_2$ production via a water electrolysis system the cost is approximately €22.5 thousands/kg$H_2$/day, while for the same capacity but for gaseous $H_2$ offsite production it drops to €13.4 thousands/kg$H_2$/day. For large HRSs, liquid $H_2$ delivery the report suggests that the cost per hydrogen quantity is lower and does not exceed €3.4 thousands/kg$H_2$/day. However, the study supports that there will be a substantial cost reduction of these values up to 50% by 2025 (Adolf et al., 2017). In this regard, industrial companies in the field of hydrogen refuelling infrastructure development have already launched stations with dispensing capacity of more than 500 kg$H_2$/day per dispenser meaning that large HRSs with two or more dispensers will contribute to a further reduction of the $H_2$ fuel cost in shorter time than expected (NEL ASA, 2018).

The ‘California Energy Commission’ in its 2015 report presented data on the capital costs of the operating and future HRSs based on the type of the station (on-site, off-site hydrogen production). According to the report, the capital cost of operating on-site stations in 2015 ranged between €2.24 million and €4.11 million, while for stations with $H_2$ delivery, the capital cost ranged from €1.72 million to €2.90 million. The projected capital costs of on-site and off-site GH2 delivered HRSs is reported to be €1.87 million and €1.42 million respectively in 2020, while for a LH2 delivered station, the cost increases to €2.27 million. The respective investment costs for 2025 is argued to be €1.25 million, €0.98 million, and €1.51 million (McKinney et al., 2015).

Robinius et al. (2018) published a report for the hydrogen mobility prospects in Germany. The report includes different scenarios of FCEVs’ penetration in the Germany transportation market indicating FCEVs’ numbers per scenario equal to 0.1 million, 1 million and 20 million FCEVs by 2030 (Robinius et al., 2018). The HRS’s costs are calculated based on data from Bonhoff (2016), who suggests a current cost of €1.0 million for Germany, with a prospect to be reduced by 40% by 2020 (Bonhoff, 2016). Additionally, the hydrogen stations’ capacity is assumed to increase for each scenario from 212 kg$H_2$/day to 420 kg$H_2$/day and 1000 kg$H_2$/day to support the respective FCEVs’ fleet. According to the report’s results, the investment cost for each scenario ranges approximately from €1.0 million to €2.2 million. In the case of 20 million FCEVs by 2030, Robinius et al. indicated a required number of 6,977 HRSs, while for the offsite $H_2$ production sites suggested a requirement of 3,000 trucks and 12,400 km of pipelines. The respective cost for the development of this infrastructure is calculated to €2.2 million/HRS, €800 thousand/truck, and €475.8 thousand/km pipeline (Robinius et al., 2018).

The cost estimations made by 'Hydrogen Council' do not differ significantly from the above-mentioned studies. Based on the report's findings, the development of adequate infrastructure to support the growing fleet of FCEVs in the future will require investment equal to €1,200 - €2,000 per FCEV until 2030, while after 2030 this cost is expected to drop to €1,000 per FCEV. In this context, developing a refuelling infrastructure of 15,000 stations to support 15 million FCEVs will require approximately €16 billion (€0.9 million to €1.2 million per large HRS). Compared to current costs of HRSs in Germany, which is €1.0 million/small HRS, and in Japan where the cost is much higher (i.e. €2.4 million to €4 million/HRS), it is apparent that by 2030 the cost of building a HRS will reduce significantly (Hydrogen Council, 2017b). In addition, Isenstadt and Lutsey (2017), support this reduction of HRSs' investment due to increase of the FCEVs' fleet, to values lower than €1.0 million per station from current costs ranging between €2.0 and €3.0 million per station (Isenstadt and Lutsey, 2017).

A more detailed cost breakdown of the HRSs' current components is presented by Mayyas (2015). According to the given data, the cost of HRS in Europe for a small and large facility is approximately €1.0 million and €1.6 million respectively, while in japan the same costs range between €2.0 million and €4.0 million (Mayyas, 2015). The cost breakdown of the HRS's components is shown in Table 3.1.2.

Table 3.1.2. Indicative cost of HRS's components. Based on data from (Mayyas, 2015).

| HRS Component | Medium HRS Cost (thousand €) | Large HRS Cost (thousand €) |
|---|---|---|
| Compressor | 324 | 480 |
| Chiller | 162 | 200 |
| Electrical | 40 | 40 |
| Storage Tanks | 171 | 240 |
| Dispenser | 162 | 280 |
| Piping-Control-Safety | 16 | 16 |
| Labour-Other Expenses | 320 | 350 |

In the same context of classifying the HRSs based on the technology associated to hydrogen production, Agnolucci (2007), suggested that on-site medium HRSs investment cost reaches €1.9 million, while for large on-site $H_2$ production HRS this cost increases to €5.7 million (Agnolucci, 2007). Similarly, Weinert (2005) and Gielen and Simbolotti (2005), suggest that on-site large SMR-based HRS costs approximately €5.0 million, and €6.5 million respectively (Gielen and Simbolotti, 2005; Weinert, 2005).

Xu et al. (2017) presented in their published research the potential cost of HRSs depending on the daily $H_2$ fuel capacity in Shenzhen in China. Based on the provided data, a small station (i.e. 100 $kgH_2$/day) presents a capital cost of €0.93 million, a medium capacity station (i.e. 500 $kgH_2$/day) has a capital cost of €3.70 million, while for a large HRS (i.e. 1000 kg$H_2$/day), the cost would rise up to €6.98 million (Xu et al., 2017).

The development of $H_2$ transportation via pipelines in the Netherlands has been investigated by Smit et al. (2007), indicating a growing trend in distribution pipelines for HRSs beginning from late 2010s to 2050. According to the study's results, this pipeline network will expand by 2030 to 5,000 km, and will reach 18,000 km by 2050. The annual investments required to develop this $H_2$ distribution grid reaches €3.8 billion (Smit et al., 2007).

The electric vehicle transportation centre (EVTC) through a report compiled by Qin et al. (2017), has also performed a financial evaluation on the capital costs of HRSs to be installed in the next 5 to 10 years. HRSs in the report are distinguished according to their capacity and the type of hydrogen production (i.e. off-site, on-site). The results of the capital investment for each case are presented in Table 3.1.3, where it is observed that for the short term forecast, the cost of off-site $H_2$ production HRSs, will be lower compared to on-site production (Qin et al., 2017).

Table 3.1.3. Capital cost of HRSs by type and capacity. Based on (Qin et al., 2017).

| **HRS Capacity (kg$_{H2}$/day)** | **HRS Type** | | | |
|---|---|---|---|---|
| | **On-site SMR (M€)** | **On-site Electr. (M€)** | **GH2 Delivery (M€)** | **LH2 Delivery (M€)** |
| 100 | 0.9 – 2.6 | 1.0 – 2.6 | 1.1 – 1.8 | 0.7 – 2.1 |
| 480 | 1.9 – 4.6 | 1.9 – 5.4 | 1.9 – 2.4 | 1.5 – 2.9 |
| 1000 | 3.2 – 4.8 | 4.0 – 7.9 | 3.2 | 2.4 |

Brown et al. (2013), on the other hand, included in their research for the hydrogen infrastructure in California, the O&M costs of a HRS. Compared to (Qin et al., 2017), the capital investment of a medium off-site HRS with LH2 delivery is at the low end at €1.6 million, while for a small off-site HRS with GH2 delivery the cost is lower to €0.8 million. The annual O&M costs for both investigated types of stations has been estimated to €81 thousand. To this end, the authors assumed that the new HRSs that are going to be constructed in the short term will comprise mostly off-site $H_2$ production refuelling spots (Brown et al., 2013).

A detailed report concerning the capital costs of HRSs and the dispensing cost of the $H_2$ fuel is published by NREL in 2013. The authors of this report, Melaina M. and Penev M., analysed data for the 2013 costs of HRSs and how are going to evolve in the near term. The report investigates similarly to other studies different categories of HRSs based on their capacity and type. Table 3.1.4 summarises the future capital costs given by Melaina and Penev (2013) and McKinney et al. (2015).

Table 3.1.4. Capital cost of HRSs (2020-2025). Based on (McKinney et al., 2015; Melaina and Penev, 2013).

| **HRS Capacity ($kg_{H2}$/day)** | **HRS Type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **On-site SMR (M€)** | | **On-site Electr. (M€)** | | **GH2 Delivery (M€)** | | **LH2 Delivery (M€)** | |
| | 2020 | 2025 | 2020 | 2025 | 2020 | 2025 | 2020 | 2025 |
| 100 | 5.9 | - | 1.9 | 1.3 | - | - | - | - |
| 180 | - | - | - | - | 1.4 | 1.0 | - | - |
| 350 | - | - | - | - | - | - | 2.3 | 1.5 |
| 400 | 1.1 | - | - | 1.2 | - | - | - | - |
| 1000 | 2.2 | - | - | 2.4 | - | - | - | - |

According to the results presented in Table 3.1.4, the most cost efficient types of HRSs in terms of capital investment are the off-site GH2 and LH2 delivery stations. Particularly, for small HRSs GH2 delivery case presents the lower initial cost in 2020, while for larger stations in 2025, liquid $H_2$ transportation is considered to be also cost beneficial. However, as NREL suggests, in the near-term, the on-site $H_2$ production HRSs will be highly competitive, especially for medium to large capacity stations.

*3.1.3.2.1.a. Discussion on the forecasted evolution of HRSs capital cost*

By taking into account the above quoted studies, Fig. 3.1.13 presents the aggregated data showing the evolution of the capital investment costs of HRSs. Due to the different types of HRSs concerning their capacity and $H_2$ delivering options, the respective capital costs, which have been used in Fig. 3.1.13 were derived from the mean values of each study based on the year that the forecasts apply for.

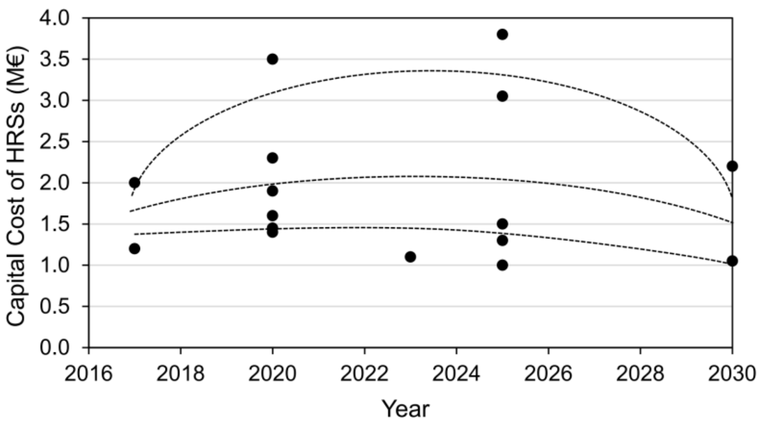



Fig. 3.1.13. Future evolution of HRSs' mean capital cost based on different forecasts. Based on (Adolf et al., 2017; Hydrogen Council, 2017b; IEA, 2015; McKinney et al., 2015; Melaina and Penev, 2013; Robinius et al., 2018).

It can be observed from Fig. 3.1.13 that the capital cost evolution of HRSs seems to follow three major trend lines, which indicate an increase by mid-2020s, while after 2025 forecasts show that it will decrease. This can be justified from the fact that compared to contemporary HRSs where the vast majority of $H_2$ is delivered from central production units, in the near future the HRSs' type will move to on-site production schemes via RES, resulting to an increased investment cost. Additionally, for the high increase scenario, moving to on-site HRSs may increase further the cost through the transition also to larger HRSs' topologies with higher dispensing capacity. However, this cost is expected to reduce in all scenarios due to economies of scale through the implementation of more HRSs by 2030.

#### 3.1.3.2.2. Cost of hydrogen fuel

The competitiveness of hydrogen as a fuel compared to other 'green' and conventional technologies in the transportation sector is of great importance in the development of the hydrogen infrastructure. For this reason, several researches have been published during the last decade indicating the significance of the retail price of hydrogen fuel to the final consumer.

Apart from data concerning the capital investment cost of HRSs, IEA suggested that the retailed cost of the hydrogen fuel will be impacted by economies of scale in the future. It is estimated that the current average price of 9.8 €/kg$H_2$ for small hydrogen stations (i.e. 100 kg$H_2$/day) will be reduced as low as 3.6 €/kg$H_2$ for future large HRSs (i.e. 1000 kg$H_2$/day) (Weeda and Elgowainy, 2015).

Viesi et al. (2017) investigated the cost of $H_2$ production and transportation to HRSs along with $H_2$ distribution cost from 2020 to 2050 for different HRS categories. The HRSs have been divided to those with very small capacity of 50 kg$H_2$/day in 2020, to small HRSs in 2030 of 100 kg$H_2$/day and to medium-large in 2050 of 500 kg$H_2$/day. In terms of HRS technology, the HRSs were categorised to those with on-site $H_2$ production from either RES alone or grid-connected water electrolysis, and those of centralised $H_2$ production from either SMR or water electrolysis. The total retail cost of $H_2$ equals to the sum of all the above costs. The results of the study revealed an $H_2$ cost range between 5.9 €/kg$H_2$ and 16.4 €/kg$H_2$ in 2020, 5.4 €/kg$H_2$ and 15 €/kg$H_2$ in 2030, and 5.8 €/kg$H_2$ and 16.8 €/kg$H_2$ in 2050. According to the study, the most cost competitive technologies comprised the centralised large scale SMR, and the on-site RES-based water electrolysis $H_2$ production topologies (Viesi et al., 2017). It should be mentioned however, that these values correspond to a case study based on hydrogen deployment in Italy.

McKinney et al. (2015) presented through their report regarding the hydrogen infrastructure in California, data concerning the $H_2$ fuel cost in HRSs under operation, as well as the future evolution of these retail prices until 2025. The prices are categorised based on the type and capacity of the stations.

In 2015, real data from operating stations showed $H_2$ fuel prices ranging between 8.8 €/kg$H_2$ and 29.7 €/kg$H_2$. On-site $H_2$ production stations presented the highest range of hydrogen prices between 16.3 €/kg$H_2$ and 29.7 €/kg$H_2$, while for LH2 and GH2 delivery stations the hydrogen price was documented between 8.8 €/kg$H_2$ and 12.3 €/kg$H_2$. The projected average $H_2$ fuel cost for 2020 and 2025 was forecasted to be 11.2 €/kg$H_2$ and 9.9 €/kg$H_2$ respectively (McKinney et al., 2015).

Melaina and Penev (2013) included also in the NREL report indicative costs of the $H_2$ fuel supplied by the on-site hydrogen production HRSs. According to the provided results, the $H_2$ retail cost in 2020 for an on-site SMR station will range between 3.2 €/kg$H_2$ for large HRSs and 6.1 €/kg$H_2$ for small capacity stations. On the other hand, the respective costs of $H_2$ fuel in 2025 supplied via an on-site $H_2$ water electrolysis production will be higher ranging from 4.5 €/kg$H_2$ for large stations to 7.7 €/kg$H_2$ for small HRSs (Melaina and Penev, 2013). The results acquired are included in Table 3.1.5.

Table 3.1.5. Near-term retail $H_2$ fuel cost for on-site HRSs' topologies. Based on (Melaina and Penev, 2013).

| HRS Capacity (kg$H_2$/day) | HRS Type | |
|---|---|---|
| | **$H_2$ fuel cost on-site SMR (€/kg$H_2$) (2020)** | **$H_2$ fuel cost on-site Electr. (€/kg$H_2$) (2025)** |
| 100 | 6.1 | 7.7 |
| 400 | 3.6 | 5.1 |
| 1000 | 3.2 | 4.5 |

In contrast to Linnemann and Wilckens (2007), who suggest a hydrogen fuel production cost for on-site water electrolysis HRS equal to 18 €/kg$H_2$ (Linnemann and Steinberger-Wilckens, 2007), Le Duigou et al. (2013), published results from the '*HyFrance3*' project indicating production cost of $H_2$ in an on-site HRS via water electrolysis supplied exclusively from wind energy up to 17 €/kg$H_2$. However, in the case where the topology includes also additional grid connection, the fuel cost could drop to 11.5 €/kg$H_2$ (Le Duigou et al., 2013).

On the other hand, in the case of hydrogen delivery from a central production unit, the cost of hydrogen fuel is highly depending on the method of transportation. Shayegan et al. (2006), presented results concerning the cost of transportation via pipelines for different distances at low $H_2$ flow rates (i.e. 0.4 t $d^{-1}$). As the distance between the central $H_2$ production facility grows, the cost of $H_2$ delivery increases. Specifically, the authors suggested that for 20 km distance the cost reaches 13.7 €/kg$H_2$, for 40 km the cost rises to 25 €/kg$H_2$, and for 60 km distance the $H_2$ delivery cost exceeds 36 €/kg$H_2$. In contrast, for these relatively short distances, delivery of $H_2$ fuel via tube trailers or road liquid tankers, costs much lower reaching 4.5 €/kg$H_2$ and 10.2 €/kg$H_2$ respectively. Based on the results, the use of pipelines for distances between 20 km and 60 km is not cost efficient compared to road transportation. However, in the case of higher $H_2$ flow rates, the delivery cost of $H_2$ fuel via pipelines is substantially lower than road delivery (Shayegan et al., 2006).

Furthermore, another study by the same scientific team presented results for different investigated scenarios on $H_2$ fuel retail cost for different HRSs' categories. The scenarios took into account different parameters comprising the evolution of $H_2$ demand, the energy prices, and the technological development for 2020 and 2025. The scenario where all the aforementioned parameters presented low growth (i.e. pessimistic scenario), indicated a hydrogen fuel cost range between 3.4 €/kg$H_2$ and 11.4 €/kg$H_2$ for 2020, and 2.3 €/kg$H_2$ and 8.0 €/kg$H_2$ for 2025. The least cost is observed for on-site SMR HRS, while the highest for pipeline delivery to off-site HRSs (Shayegan et al., 2009).

Brown et al. (2013), presented also the $H_2$ fuel cost for GH2 and LH2 delivery to off-site HRSs to be built in the near-term, based on the hydrogen demand of a growing FCEVs' fleet. The fuel costs for each case are included in Table 3.1.6 (Brown et al., 2013).

Table 3.1.6. Retail cost of $H_2$ based on the demand. Based on (Brown et al., 2013).

| Share of FCEVs in vehicles' fleet (%) | HRS Type | |
|---|---|---|
| | $H_2$ fuel cost off-site GH2 (€/kg$H_2$) | $H_2$ fuel cost off-site LH2 (€/kg$H_2$) |
| 10 | 10.4 | 10.7 |
| 20 | 9.4 | 8.1 |
| 50 | 8.6 | 7.2 |
| 100 | 8.1 | 6.8 |

In the same context of $H_2$ retail price, McKinsey & Co (2010), discussed the prospects of cost reduction and presented forecasts of how the $H_2$ fuel cost is going to evolve by 2050. This report however, due to the time it was published it assumes that the current cost (2017 values) of hydrogen fuel would be approximately 7.7 €/kg$H_2$ which is rather optimistic. For this reason, the authors suggest that the average retail price of $H_2$ at the dispenser will reach 6.6 €/kg$H_2$ by 2020, 5.0 €/kg$H_2$ by 2030 and 4.4 €/kg$H_2$ by 2050. Although the 2020s' value seems that it will not be verified, the other estimations are similar to other contemporary studies (McKinsey & Co, 2010).

The cost of hydrogen fuel in USA in 2040 is forecasted by Morrison et al. (2018), showing a value of 2.2 €/kg$H_2$, which compared to other studies concerning 2050, is lower (Morrison et al., 2018). Compared to that, Emonts et al. (2019), presented different scenarios for Germany in 2050 regarding a respective hydrogen market in transportation. The range of the $H_2$ fuel price is documented to be in the range of 6.0 €/kg$H_2$ to 9.9 €/kg$H_2$ (Emonts et al., 2019).

Xu et al. (2017), following their study on the prospects of developing a network of HRSs to support a growing fleet of FCEVs in Shenzhen in China, presented a financial evaluation of the project concerning small, medium, and large HRSs. The derived breakeven $H_2$ prices for having a feasible within 20 years return of the investment, showed values of 6.9, 6.2 and 6.0 €/kg$H_2$ for the small, medium, and large stations respectively (Xu et al., 2017).

*3.1.3.2.2.a. Discussion on the forecasted evolution of $H_2$ fuel cost*

Acknowledging the above, Fig. 3.1.14 summarises the mean $H_2$ fuel retail prices based on the cost ranges quoted by the described publications. Similarly to the HRSs' investment cost, fuel cost is dependent on stations' type regarding fuel delivery and capacity. For this reason, Fig. 3.1.14 depicts the mean values derived from the above-mentioned studies. According to the figure, the future cost of hydrogen fuel is to either decrease significantly by 50% or present a reduction of approximately 30% in the next 15 years. Subsequently, the forecasts show a stabilisation of the price by 2050 to values less than half of today's retail cost within a range between 4 €/kg$H_2$ and 7 €/kg$H_2$. This forecasted trendlines can be explained by the high increase of the number of HRSs (see Fig. 3.1.12) and the transition to stations of higher capacity, which will induce a fuel cost reduction. However, depending on the hydrogen market development, the reduction of $H_2$ fuel cost is expected to present different level variations.

As most of the referred studies suggest, the hydrogen fuel retail cost is forecasted to decrease by 2050 to appealing levels for supporting the transition to hydrogen-based mobility. In contemporary light duty FCEVs, hydrogen fuel consumption reaches approximately 1.0 kg$H_2$/100km and is expected to decrease below 0.7 kg$H_2$/100km by 2040 (Viesi et al., 2017). On the other hand, conventional vehicles are expected in the near future to present a fuel consumption of approximately 3.7 l/100 km (Hydrogen Council, 2017a). By taking into consideration that the cost of hydrocarbon-based fuels in Europe present an increasing trend reaching 1.44 €/l at mid- 2018 (European Environment Agency, 2018), an average running cost of conventional vehicles will be higher than 5.1 €/100km. Hence, an unsubsidised fuel price of hydrogen below 8.0 €/kg$H_2$ would suggest an average running cost below 5.6 €/100km, which will be highly competitive with conventional vehicles.

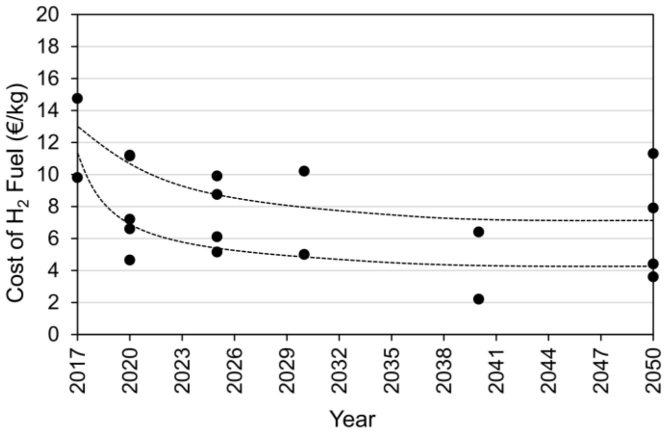



Fig. 3.1.14. Evolution $H_2$ fuel retail cost based on different forecasts. Based on (Brown et al., 2013; Emonts et al., 2019; Le Duigou et al., 2013; McKinney et al., 2015; McKinsey & Co, 2010; Melaina and Penev, 2013; Morrison et al., 2018; Shayegan et al., 2009; Viesi et al., 2017; Weeda and Elgowainy, 2015; Xu et al., 2017).

### 3.1.4 Conclusions

As a contribution to the development of an emerging hydrogen market in the transportation sector, this study comprised of a literature review regarding hydrogen infrastructure for mobility purposes. Hydrogen refuelling stations have an important role in the transition to a hydrogen based economy by supporting the penetration of $H_2$ based vehicles in the transport market. However, in order to achieve a substantial expansion of this emerging market, the network of refuelling stations must be developed simultaneously with the introduction of commercial hydrogen vehicles.

In this context, more than 370 $H_2$ stations were in operation globally at the end of 2018, out of which more than half are publicly accessible, while the others are used for demonstration/research projects, and for supplying hydrogen to private fleets. On the other hand, the global number of fuel cell electric vehicles is estimated that overpassed 12,900 in 2018, with forecasts indicating that more than 10 million private vehicles will be hydrogen powered by 2030.

The research focussed on presenting findings from peer-reviewed literature and other published scientific reports concerning the current status of hydrogen infrastructure and its future prospects in transportation. The presented results indicated that hydrogen mobility is still at an infant stage, albeit it presents promising prospects in the transition to a low-emission era in ‘green’ mobility. On top of that, nowadays most of the past technological constraints have been eliminated suggesting that at least in the technical area, hydrogen technologies are highly competitive with conventional and other “green” technologies in transportation. Hence, the outcome of this research showed the present evolution of hydrogen technologies in road transportation and examined the prospects of $H_2$ in the mobility sector towards sustainability. To this end, an analysis between different forecasts provided significant data regarding possible scenarios of HRSs and FCEVs future deployment indicating a strategic roadmap to electric-based transport.

The main conclusions suggest also that the factors associated with hydrogen deployment in transportation lie in two axes, FCEVs and infrastructure development. Currently, many countries are developing a network of HRSs in order to promote the expansion of hydrogen mobility. However, this mandates the reduction of ownership costs of FCEVs in order to economically compete with other types of low-emission vehicles. The vast majority of studies support that for most scenarios, hydrogen-based infrastructure will present a substantial growth after 2025. This will be achieved on one hand through the further technical development and cost reduction of FCEVs and on the other by lowering the necessary capital investment for building the adequate infrastructure.

In any case, it will be highly beneficial to support hydrogen infrastructure in relation to a growing fleet of FCEVs through the impetus of more research studies investigating how ‘green’ technologies in mobility may contribute in the expansion of alternative ways of transportation. Certainly, hydrogen will play a significant role in future mobility, and it will definitely support the challenging venture of a non/low emission based transportation in the near future.

## 3.2 Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark

In 2017, the transportation sector in the European Union was responsible for 27% of the total greenhouse gas emissions, of which road transportation accounted for 71.7%. As a result of the EU policy to reduce the total greenhouse gas emissions by at least 40% in 2030 compared to 1990 levels, a social acceptance of a new technology like hydrogen in transportation is important. This study investigates the factors that may affect the public's acceptance of hydrogen-powered vehicles in Denmark. To this end, four major hypotheses were stated, assuming the direct effect of factors such as technology and environmental awareness, financial status and infrastructure pertaining to the social acceptance of hydrogen-based private road vehicles in the transportation market. The results showed that most of the hypotheses can be confirmed, including environmental awareness, limited refuelling infrastructure as well as media support for this market. These factors can be said to have an impact on one's willingness to accept or even purchase a fuel cell electric vehicle in the near future, while knowledge of and prior experience with this type of technology, along with an upgrade of the hydrogen refuelling infrastructure, may prove to contribute positively to 'greener' transportation.

### 3.2.1 Introduction

One of the greatest challenges of our time that affects both the environment, the ecosystem in total and, of course, the economy comprises the prevention of the global climatic change (United Nations, 2019a). Many countries, including the EU, have committed to reduce their GHG emissions via the Kyoto Protocol, which in its 2nd commitment period have set a target of reducing GHGs by at least 18% below 1990 levels by 2020 (United Nations, 2020). However, the total GHG emissions of the OECD countries have increased since 1990 from 15.17 Gt $CO_2$-eq to 15.43 Gt $CO_2$-eq in 2017. In the EU-28, on the other hand, GHG emissions have been reduced from 5.65 Gt $CO_2$-eq to 4.32 Gt $CO_2$-eq, respectively, with the highest decrease in the energy industries (i.e. from 1.67 to 1.18 Gt $CO_2$-eq), while in contrast, GHG emissions from transportation have increased from 0.79 to 0.94 Gt $CO_2$-eq (OECD, 2019a).

Hence, the transportation sector is one of the main contributors to GHG emissions in the EU-28, accounting for 27% (including aviation) of the total GHG emissions in 2017, of which 71.7% were directly linked to passenger cars and vans (European Commission, 2020b). Fig. 3.2.1 shows the share of GHG emissions by sector for the EU-28 in 2017.

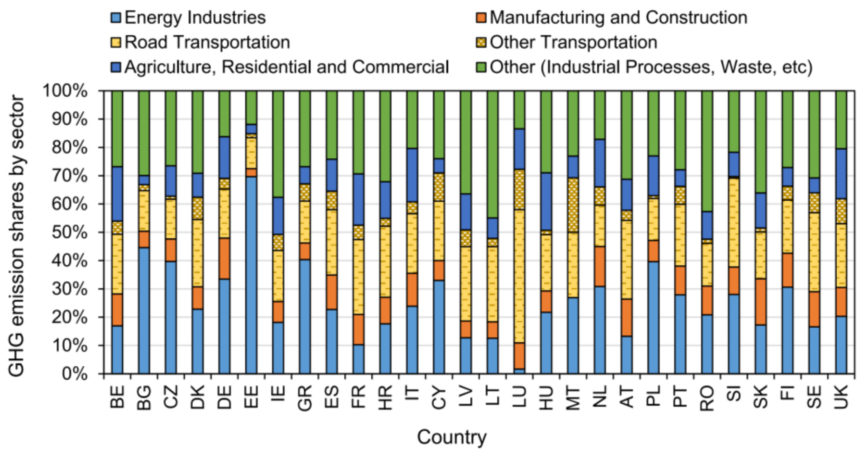



Fig. 3.2.1. EU-28 GHG emission shares by sector in 2017. Based on (European Commission, 2020b).

It is apparent from Fig. 3.2.1 that the energy industries and the transportation sector in the vast majority of the EU-28 exceed 50% of the GHG emissions. However, by taking into account the efforts to decarbonise the energy sector over the last decades by integrating RES, it would be highly beneficial to move towards similar pathways in the transportation sector, too.

According to Fig. 3.2.2, there were 13 EU countries in 2017 with road transportation emissions share above the average (i.e. 21.6%). The transportation emissions are aligned with the rest of the carbon intensity sectors presented in Fig. 3.2.1, meaning that in the case of lower emissions from the energy industries, the share of transportation in total emissions increases accordingly. However, by also taking into account on-road emissions per capita (see Fig. 3.2.2), in countries where the average transportation emission share in total GHG emissions is exceeded, the average on-road emissions per capita of approximately 2.5 $tCO_2$-eq/capita is not. In total, seven out of 28 countries presented higher on-road emissions per capita in 2017, of which only three did not emit more than the average share of road transportation emissions. Hence, it can be assumed that the total emissions from road transportation in the remaining four countries are more significant compared to the rest of the EU-28.

In 2017, transportation in Denmark (excluding international maritime) accounted for the highest share among all sectors, reaching approximately 31.7% of the total emissions, of which 75.1% stemmed from road vehicles (European Commission, 2020b). Denmark ranked 9th among the countries with higher-than-the-average road transportation-induced GHG emissions in 2017 and was one of the four countries with higher-than-the-average road transportation shares of the total emissions and on-road emission ratios per capita.

The goal for Denmark is to be free of fossil fuels in 2050 (Energistyrelsen, 2016), and considering the fact that conventional fuels still play a significant role in Denmark, it is required to adopt alternative solutions supporting sustainability and low GHG emissions. To this end, the transportation sector could substantially contribute to the country's decarbonisation targets through the implementation of new vehicle technologies that are environmentally friendlier than conventional technologies.

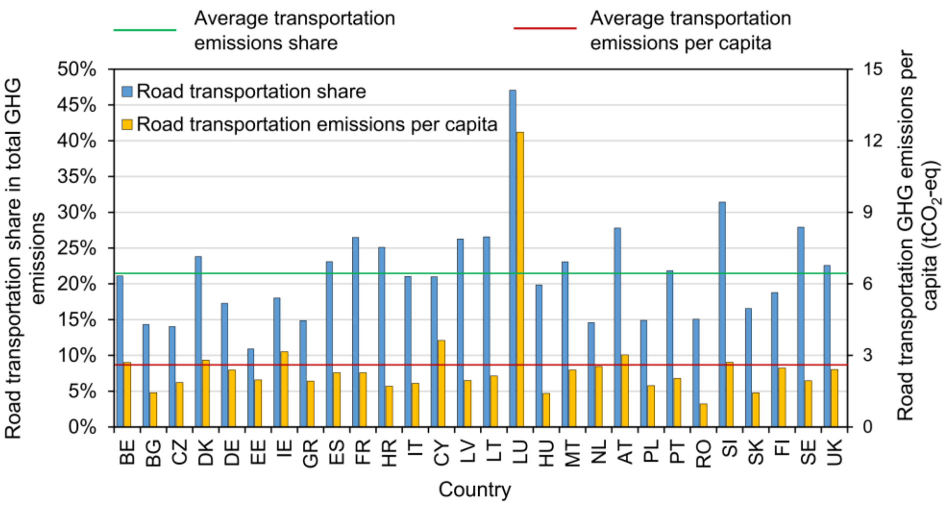



Fig. 3.2.2. Share of road transportation of the total EU-28 GHG emissions and road transportation emissions per capita in 2017. Based on (European Commission, 2020b; Eurostat, 2019b).

All the above indicate that there is a need for using alternative technologies in the mobility sector, such as electric vehicles, which, compared to conventional technologies, present zero direct GHG emissions. The public is already aware of the greener alternative of BEVs, although there are still some drawbacks that hinder their further deployment, including high investment costs, short traveling range, limited recharging infrastructure and fossil fuel-based electricity, minimising the sustainable benefits of the technology (Priessner et al., 2018). Based on the EAFO (EAFO, 2019b), it can be derived that although the number of BEVs increased from several hundred in 2008 to hundreds of thousands (≈ 750,000) in 2019, the annual increasing rate of new registrations has been hindered and seems to have stabilised since 2016 to approximately 40-50%. The rapid pace of integrating BEVs in the transportation vehicle market is challenged by the drawbacks that contemporary BEVs still present compared to conventional vehicles. From a consumer perspective, BEVs are still more expensive than their conventional counterparts, they have shorter driving range, high recharging times and an inadequate recharging infrastructure, which do not favour their expansion (Carley et al., 2019; Coffman et al., 2017; Hardman et al., 2018).

An upcoming and already almost established fuel alternative for vehicles is hydrogen (Apostolou and Xydis, 2019). Hydrogen vehicles have been found to present a three times lower global warming potential than other alternative technology counterparts (Bicer and Dincer, 2017). Contemporary vehicles running on on-board stored hydrogen use a fuel cell to chemically convert hydrogen energy into electricity, which usually powers the electric motor while charging an on-board buffer battery bank. The buffer battery is mainly used to support high power demand and as an energy storage device during regenerative braking of the vehicle (Wang et al., 2019).

The use of hydrogen as fuel is gradually being developed, especially FCEVs, which provide several benefits in terms of some of the factors that BEVs struggle to overcome, e.g. higher driving range and fast refuelling times (Adolf et al., 2017; Apostolou and Xydis, 2019; Thomas, 2009). Although the increase in such vehicles in Europe between 2014 and 2019 exceeded a percentage of 1000%, their absolute number is still a very small fraction of the total alternative vehicles, reaching 1,286 vehicles in 2019 (including busses and light commercial vehicles) (EAFO, 2019c). Therefore, it would be important to locate all the reasons affecting the further expansion of this technology. A major factor supporting the establishment of a new technology includes the social acceptance of the public. Through an empirical study, this paper investigated the social acceptance of FCEVs in Denmark and the factors that might influence the willingness to purchase such a vehicle.

Nowadays, the use of hydrogen as an alternative technology in transportation compared to BEVs is not supported by the public media, which instead, portray BEVs as the only sustainable choice for the future transportation sector. The question is, however, whether a BEV is more sustainable than a FCEV. Would it not make sense to use both types instead of BEVs only? Is the public lacking knowledge and awareness of hydrogen vehicles as an alternative, or is it the current infrastructure and political commitment that does not support hydrogen mobility as the next sustainable technology?

The following section consists of a literature review and describes previous studies that have been associated with public acceptance of hydrogen technologies as well as the factors and their potential influence on a successful market penetration. In addition, the hypotheses used in this paper to determine the factors that may influence the social acceptance of the public are included in the second section.

The third section includes the methods and setting for the data collection as well as the analysis of the data. Finally, the fourth section presents the results and discussion of the analysis and whether the stated hypotheses from the second section can be confirmed or rejected.

#### 3.2.1.1 Literature review

Since the introduction of the first commercialised FCEV in the transportation market in early 2015, the automotive industry's interest is growing towards the development of FCEVs in line with other electric vehicle types. Although there are currently three hydrogen passenger car models available in the vehicle market, their share in this market is still at an initial stage (Apostolou and Xydis, 2019). This is further enhanced by the fact that the availability of such vehicles in the market is limited as being a new vehicle technology with inadequate infrastructure support in many countries. In the last half-decade, several studies in the peer-reviewed literature analysed factors affecting the penetration of the FCEVs in the transportation market. However, these studies either encountered only specific issues such as ownership costs and lack of infrastructure or documented a comparison of FCEVs with other alternative vehicles from a social perspective. Additionally, these studies did not take into account the media influence, without presenting at the same time forecasts concerning the expected cost of evolving hydrogen technologies and how this might affect the public willingness to purchase a FCEV.

Iribarren et al. (2016) presented the results of their quantitative research on the attitude of society in Spain in relation to the use of hydrogen in transportation. The outcome of their study was based on a survey focusing mainly on the associated costs, the required infrastructure and reliability in general. The authors concluded that there is a high level of awareness of hydrogen technologies for transportation in Spain, while infrastructure and high costs play a critical role in the willingness of the respondents to purchase a FCEV (Iribarren et al., 2016). Similarly, the attitude of consumers participating in a test process of FCEVs in the UK was assessed by Hardman et al. (2016). Although the participants stated that the FCEV driving behaviour was similar to the one of conventional vehicles, they identified that lack of infrastructure and increased investment and operating costs were significant barriers to be overcome (Hardman et al., 2016).

The prospects of AFVs, including FCEVs in the German market were analysed by Hackbarth and Madlener (2016). The results of their research revealed that fuel-tax reductions for AFVs would not affect their deployment, but instead, future vehicle buyers would consider paying extra fees to have an adequate fast recharging/refuelling infrastructure. Specifically for FCEVs, the respondents declared that they are willing to pay an extra fuel fee of 5.14 €/kg$H_2$ in order to have a sufficient number of refuelling stations (Hackbarth and Madlener, 2016).

Hardman et al. (2017) investigated from a consumer's point of view the challenges FCEVs need to cope with in order to establish their share in the market. Five key barriers were analysed in respect to the adoption of FCEVs by the public, including cost issues, infrastructure, safety, hydrogen sources and the lack of recharging from home. The research was based on personal interviews of 39 owners of BEVs in California, USA, who were asked about their opinion on FCEVs. The results showed that the most important issue is the lack of infrastructure, followed by the carbon intensity of the hydrogen production method and the challenge of home charging. The cost and safety barriers followed as less important for the participants (Hardman et al., 2017).

Based on a public survey, the Japanese public's awareness and opinion of hydrogen infrastructure were assessed by Itaoka et al. (2017). The authors compared the results with the outcome of two similar surveys conducted in 2008 and 2009 in Japan and concluded that public awareness of hydrogen technologies has increased significantly in the last decade, while knowledge and public acceptance of HRSs and FCEVs have heightened slightly due to the attention given by the media (Itaoka et al., 2017).

The social acceptance of hydrogen technologies in transportation in Japan was also documented in the research of Hienuki et al. (2019). The authors identified that knowledge about hydrogen technology contributed positively in the public attitude towards hydrogen vehicles and infrastructure, while environmental and socioeconomic benefits of the technology were assessed to present little impact to the acceptance of the new technology (Hienuki et al., 2019). In the same context, Ono et al. (2019) examined the acceptance of HRSs sited near the residence of a survey's respondents. The received data showed that safety concerns induced a reluctance of the people towards the implementation of hydrogen infrastructure near their homes, which however was overcome after the provision of quantitative risk information concerning the operation of a HRS (Ono et al., 2019).

The investigation of the public opinion and acceptance of hydrogen technology in transportation in Stavanger, Norway was performed by Tarigan et al. (2012). The authors identified that knowledge and attitude towards hydrogen transportation and refuelling stations affected the acceptance by the public. The residents living near a HRS located in the Stavanger area demonstrated an increased knowledge about hydrogen transportation, which contributed to a 'Back Yard' model implying lower support to hydrogen transportation compared to residents living in the greater area (Tarigan et al., 2012).

Bögel et al. (2018) published the results of a survey conducted in seven EU countries regarding the public attitude towards stationary and mobile hydrogen applications. The outcome of their study showed that the attitude of the respondents presented a low level of strength and stability, which however changed to the positive direction once information about the technology was provided. This indicated, according to the authors, that the dissemination of the technology characteristics to the public through proper communication strategies is crucial for increasing the acceptance of hydrogen technologies by the public (Bögel et al., 2018).

The assessment of the driving behaviour of FCEVs was investigated by Lipman et al. (2018) who examined the opinion of 54 FCEV drivers in California, USA concerning their experience compared to conventional vehicles. The results indicated that most of the drivers believed that the FCEV was 'as safe' or even safer than its conventional counterparts, the infrastructure was not an issue, and the refuelling cost was at the same level of gasoline. More than 70% of the participants declared that they were willing to pay up to $40,000 for a FCEV suggesting a high level of acceptance (Lipman et al., 2018).

Kim et al. (2019) examined the prospects of the FCEV market in South Korea in relation to the willingness of the public to purchase a hydrogen-based private vehicle. The results of the survey, which focused on the fuel efficiency, infrastructure accessibility, vehicle type and environmental benefits of FCEVs, showed that the South Korean public expressed a significant interest in this vehicle type and provided an estimation of the marginal willingness to pay per household per year. An increase in the fuel efficiency by 1 km/L, a 1% increase in assessable refuelling stations, a 1% decrease in $CO_2$ emissions and a shift to SUV instead of sedan vehicles would give a total marginal willingness to pay of approximately 12,000 €/year (Kim et al., 2019). In their study on the preferences of the South Korean public between FCEVs and BEVs, Shin et al. (2019) included two levels concerning the vehicle choice and usage among drivers and non-drivers participating in a survey. The results showed that the driver group preferred BEVs over FCEVs due to lower costs and recharging availability, while non-drivers had a higher preference for FCEVs. In terms of usage level, the driver group preferred none of the two AFVs over conventional vehicles (Shin et al., 2019).

Nie et al. (2020) studied the factors affecting the social acceptance of FCEVs in the Jiangsu province in China. The authors documented that in addition to the financial and environmental factors affecting the acceptance of FCEV technology by the public, the industrial agglomeration of a region presented a positive correlation in the propensity of the residents to purchase a FCEV (Nie et al., 2020).

Older public opinion studies on hydrogen-based transportation before 2006 and the commercialisation of FCEVs indicated that many survey participants were not very well informed and knowledge of the main characteristics of this technology was limited (Altmann and Graesel, 1998; Maack, 2005; O'Garra et al., 2005; Schmoyer et al., 2006; Zachariah-Wolff and Hemmes, 2006). However, in some cases where the participants' working environment was related to transportation, the results were different. This was the case of Dinse (2001) where workers in the BMW group were asked about their knowledge and opinion about hydrogen automotive technology, and the vast majority replied positively, but noted the high costs and the need for infrastructure investments (Dinse, 2001).

In this context, O'Garra et al. (2007) examined the willingness of the public in four major cities (i.e. Berlin, London, Luxembourg and Perth) to pay a bus fare for introducing hydrogen buses in their cities. Overall, the responses from the public were positive, showing an interest of applying hydrogen technologies in public transportation (O'Garra et al., 2007). The positive attitude towards hydrogen mobility following a FCEV test drive in California, USA, was documented by Martin et al. (2009). More than 80% of the 182 participants left with a positive impression and answered that in terms of infrastructure, they are willing to travel between five and ten minutes to find a HRS. The authors concluded that a driving experience of a FCEV would significantly affect consumers' view on hydrogen-based transportation (Martin et al., 2009). Thesen and Langhelle (2008) investigated the social awareness and attitude towards hydrogen vehicles and refuelling infrastructure in Norway. The results were compared to the outcome of a research published by O'Gara et al. (2005), who analysed the awareness and acceptability of hydrogen transportation in London via a survey of approximately 400 London residents and found that the majority of them did not know that hydrogen can be used for transportation (O'Garra et al., 2005). The survey results from the Thesen and Langhelle (2008) research, on the other hand, showed that more than 65% of the respondents had a positive opinion about hydrogen mobility, while less than 30% needed more information (Thesen and Langhelle, 2008). A similar study by Zimmer and Welke (2012) in Germany indicated that a high percentage of the German public favours hydrogen vehicles (i.e. approximately 80%) firstly, due to environmental reasons, secondly, to cope with future oil shortage and, finally, because they believe that hydrogen technologies could consist of an important economic factor for development (Zimmer and Welke, 2012).

The above studies show that over the last decades, hydrogen-based transportation has gradually gained the acceptance by a major part of the public in some regions. However, compared to other AFVs, the public willingness to purchase a FCEV is still low, mainly due to cost and refuelling infrastructure barriers.

#### 3.2.1.2 Research Objectives

The objective of this research was to appraise the prospects of the FCEV market and how these are affected by factors associated with the technological and social perspectives. Denmark is among the first countries where RESs and particularly wind power have been developed significantly since 1990. Nowadays, most of Denmark's electricity demand is covered by wind energy (Hvelplund et al., 2017) as a result of the policies adopted in recent decades towards a more sustainable environment. In this context, the transportation sector, which plays a substantial role in supporting the transition to a non-fossil fuel era (see Fig. 3.3.2), needs to adopt new technologies free of GHG emissions. As mentioned above, one of the most interesting AFVs is the FCEV. However, although the first commercial private vehicles are available in the market of some countries (e.g. Denmark), the public seems reluctant to use this technology.

Therefore, this paper aims to identify the reasons that keep Danish consumers sceptical about purchasing FCEVs and assess possible interactions between factors affecting the public opinion. Furthermore, the methodology applied in this study could be used as a pilot for further research on the reasons lurking under the slow expansion of this promising market. To this end, a number of hypotheses is stated about the factors that may influence consumers' willingness to accept hydrogen cars as the next sustainable choice in the transportation sector.

### 3.2.2 Theoretical basis and hypotheses

This study was partially based on the technology acceptance model 3 (TAM3) developed by Venkatesh and Bala (2008), which was firstly used for the acceptance of new IT technologies (Venkatesh and Bala, 2008). Several studies, however, have also adapted the TAM3 to assess the acceptance of new vehicle technologies such as BEVs (Dudenhöffer, 2013; Globisch et al., 2018; Hamidu, 2017; Stanton, 2017). TAM3 provides some important advantages over other developed models, including the investigation of the consumer's PU and ease of use PEOU of a technology. Although TAM3 model includes constructs such as 'behavioural intention' and 'use behaviour', these factors were not taken into consideration and only PU and PEOU were used to reach the final outcome of this research indicating the public acceptance towards this technology. The model was based on a set of hypotheses aimed at describing the social aspects of hydrogen-based mobility in the Danish transportation market.

The PEOU and PU in this study could be addressed as:

PEOU: Knowledge and experience with the FCEV technology plays a critical role in PEOU and directly affect the willingness to purchase a FCEV.

PU: The environmental benefits arising from the use of a FCEV (acquired through technology knowledge) in conjunction with the environmental attitude and PEOU of each individual could affect the willingness to purchase such a vehicle.

The relations between the PU and PEOU and the main objectives of this study can be observed in Fig. 3.2.3.

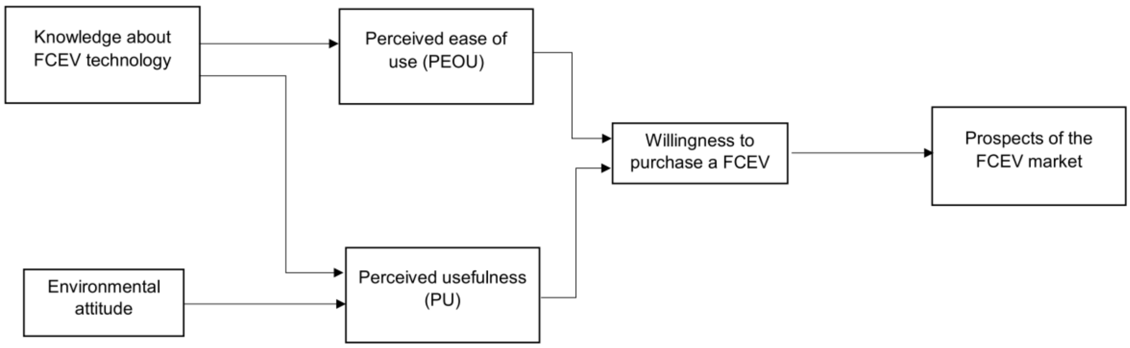



Fig. 3.2.3. General model showing the main relations between the PU, PEOU and the objectives of this study.

The next part of this research identified the factors affecting the different stages of the model presented in Fig. 3.2.3 and developed the hypotheses to assess the prospects of the FCEV market in Denmark.

### 3.2.2.1 Individual consumer awareness

The discussion of hydrogen as an alternative fuel for vehicles relates to consumers' environmental responsibility in their daily lives as well as in their energy and other consumption patterns. People today have a different awareness of the environmental impact, especially in relation to their everyday habits. Since hydrogen can be a RES in the transportation sector, the individual's attitude towards the global environmental problems may affect one's consumption patterns, including the propensity to switch from petrol or diesel vehicles to an environmentally friendlier alternative. This is also substantiated by the findings in (Ziegler, 2012), which describe that respondents who usually buy environmentally friendly products also have a significantly higher tendency to choose hydrogen and electric vehicles. Based on this, the following hypothesis about consumers' PU is expressed:

*Hypothesis H1: There is a correlation between one's attention and awareness of environmental impacts and the willingness to purchase a hydrogen-based vehicle.*

### 3.2.2.2 Knowledge and prior experience

Moula et al. (2017) suggested that one of the major issues among successful market penetration of new technologies is the knowledge of the subject and to some extent also the previous experience that one may have with this technology (Moula et al., 2017). Although the primary technology studied in their research was the use of biofuels in the transportations sector, it can be compared with the overall situation of introducing a new technology to the market, which in this case is the reduction of fossil fuel use that currently dominates in the transportation sector by using hydrogen as an alternative. Some of the results demonstrated in (Moula et al., 2017) explain that before the respondents could be motivated to switch to a more renewable-oriented consumption, they would need further information on the subject that could affect their PU and PEOU. Ziegler (2012) also explained that consumers who already had experience with a specific type of technology would have a shorter 'psychological distance' for adopting this technology (Ziegler, 2012). To this end, consumers would recognise the technology's usefulness, and previous experience with AFVs would substantially influence the FCEV market growth.

Non-experience and lack of the respective technology knowledge behind FCEVs can raise several safety concerns to potential market adopters. Due to its intrinsic characteristics, hydrogen is sometimes considered to be dangerous by the public (Ball and Wietschel, 2009; Huijts et al., 2012; Keles et al., 2008; Yetano Roche et al., 2010), and therefore, this attribute may adversely affect future consumers to purchase a FCEV.

Therefore, the following hypotheses are stated:

*Hypothesis H2: The individual person's knowledge of hydrogen technologies has an effect on the willingness to purchase a hydrogen vehicle.*

*Hypothesis H2.1: Prior experience with AFVs or FCEVs contributes to the knowledge of the technology and has an influence on one's willingness to purchase a hydrogen vehicle.*

*Hypothesis H2.2: Hydrogen safety concerns have a negative impact on the acceptance of hydrogen mobility by the public.*

#### 3.2.2.3 Price and efficiency

Two of the major concerns when purchasing a new vehicle are the ownership costs and the traveling range of the vehicle in order to meet a person's driving needs. The regular car owner already knows approximately what the traveling range is for a normal fossil fuel car, and by taking an average fuel consumption of contemporary cars in Denmark equalling to 5.2 L/100 km and a fuel tank with an average volume capacity of 45 litres, the traveling range would be approximately 850-900 km per full tank (IEA, 2019b; Rosengren, 2018). In comparison, a FCEV with a tank capacity of 5-6.3 kg$H_2$ of hydrogen has a traveling range of 500-750 km (H2.LIVE, 2020). In large numbers, one kilogram of hydrogen can replace approximately 6.5 L of gasoline in terms of fuel consumption, and with the retail price of one kilogram of hydrogen and one litre of petrol being approximately 9.5 €/kg$H_2$ (H2.LIVE, 2020, p. 2) and 1.39 €/L (My LPG, 2020) respectively, the fuel cost of a FCEV compared to an average conventional passenger vehicle is approximately the same. As Moula et al. (2017) suggest, the price of fuel is directly linked to the public's acceptance according to the consumer's consumption behaviour in the transportation sector.

Another important factor when deciding to purchase a vehicle is the initial capital investment, as explained in the paper by (Keles et al., 2008). In addition, a price reduction to a so-called 'normal' price range is also important when discussing consumer acceptance of FCEVs. At present, passenger FCEVs have an unsubsidised price of approximately €69,000 to €78,500 (H2.LIVE, 2020), while an average price of a new conventional passenger vehicle in Denmark ranges from €22,500 to €40,000 (IEA, 2019b). This is a major price difference, which might play a critical role in the decision of the public to purchase a FCEV.

Nevertheless, the future prospects of hydrogen-based vehicles globally is expected to grow significantly in the next decade, with some studies even showing a magnitude of several million vehicles (Apostolou and Xydis, 2019; Hydrogen Council, 2017a) compared to approximately 13,000 in early 2019 (IEA, 2019a). To this end, the retail prices for future FCEVs is expected to decrease due to economies of scale and advancements in fuel cell technology. The U.S. Department of Energy has set a goal of reducing the cost of the main component of a FCEV (i.e. fuel cell stack) from approximately 170 €/$kW_{net}$ today to 40 €/$kW_{net}$ by 2025 (James, 2019). Based on this, the retail price of FCEVs is expected to decrease compared to current prices by 50% in 2030 and be fully comparable to those of conventional vehicles (Creti et al., 2015).

In the same context, the retail price of the hydrogen fuel is expected to decrease ranging between 6 and 8 €/$kgH_2$ by 2030, depending on the type of HRS and the hydrogen production source (Apostolou and Xydis, 2019). On top of that, according to forecasts by the World Bank and the IEA, crude oil prices are expected to increase by approximately 16% by 2030, resulting in a simultaneous increase in retail prices (EREA and DEA, 2019; World Bank, 2019). To this end, the difference in fuel expenses between conventional vehicles and FCEVs in the next decade would most likely be expanded.

By comparing the above, the following hypotheses are expressed:

*Hypothesis H3: The fuel efficiency and refuelling cost of hydrogen vehicles influence people's propensity to choose a hydrogen vehicle.*

*Hypothesis H3.1: The capital cost of hydrogen vehicles is an important factor in the population's acceptance of hydrogen vehicles in the future.*

*Hypothesis H3.2: Future reduction in capital and refuelling costs of a hydrogen vehicle will enhance the hydrogen transportation market.*

#### 3.2.2.4 Awareness and public acceptance

As with many new technologies that have not yet penetrated the market successfully, public acceptance can be crucial to consumer acceptance by looking at the PEOU of the particular technology (Ziegler, 2012). The factors that might influence the consumers' willingness to accept and purchase a hydrogen vehicle are information and advertising from the media, the available infrastructure (e.g. number of refuelling stations) and, as linked to the previous section, the ownership costs.

Moula et al. (2017) discussed how the availability of HRSs has an increasing effect on the attractiveness of FCEVs for the consumer. This indicates that the deployment of hydrogen technologies in transportation is similar to the chicken and egg problem stating that this market is highly dependent on the number of refuelling stations as well as on-road vehicles (Apostolou et al., 2019). Hence, retail sales of and consumer demand for FCEVs have an impact on the number of refuelling stations, as this is a matter of supply and demand (Keles et al., 2008). Therefore, public acceptance encouraged by policy measures and government initiatives to make these stations more accessible may have a major effect on the successful market penetration of these types of vehicles (Ziegler, 2012). So far, there are a total of eight HRSs in Denmark, of which seven are available to the public, while another two are under construction, including one for a bus fleet in the city of Aalborg (Brintbiller, 2020). Although the number of hydrogen stations is lower compared to other countries, Denmark is considered to have the first hydrogen refuelling network able to cover the hydrogen fuel demand of a FCEV to travel in its entire region (Brintbiller, 2020). However, the PEOU of FCEVs in conjunction with the infrastructure constraints might have a direct effect on the evolution of hydrogen mobility.

Another perspective relates to the media's orientation towards passenger AFVs. In Denmark, the media focus mostly on BEVs and PHEVs, which in 2019 reached a number of 14,851 and 7,305, respectively, compared to only 101 FCEVs (EAFO, 2019c). The infrastructure and consumers' awareness of the electric alternatives have rapidly increased as media focus has intensified over the years. Ziegler (2012) explains that proactive information and advertising influence of the future consumer acceptance, which would mean a shift in the alternative vehicle market or the introduction of hydrogen-powered vehicles in the existing Danish vehicle market.

Overall, it is apparent that the transition to implementing hydrogen technologies in mobility necessitates support schemes stemming from the media and governments. Hence, the following hypotheses can be compiled:

*Hypothesis H4: Media orientation towards hydrogen-based transportation has an effect on the public willingness to accept hydrogen vehicles as a feasible alternative.*

*Hypothesis H4.1: There are currently seven public hydrogen refuelling stations in Denmark. Hydrogen refuelling infrastructure needs to be enhanced to support a growing FCEV market.*

Socio-demographics may also affect the willingness to purchase a FCEV in the future. In this paper, the socio-demographics have not been considered as hypothesis themselves but they were included in the theoretical model. In this context, they were analysed as factors influencing the knowledge about hydrogen mobility and therefore the PEOU of this specific technology. Additionally, socio-demographics were used for adjusting the sample size to the entire target population in order to limit bias towards more robust results (Ziegler, 2012).

### 3.2.3 Research settings and methods

For testing the stated hypotheses, an empirical study was compiled based on the collection of data from Danish consumers. The collected data were based on an online anonymous survey uploaded to Danish social media focusing on permanent Danish residents who own or use a private passenger vehicle. The main objective of this empirical study was to compute the opinion of the Danish population participating in the private transportation market through owing a passenger vehicle by analysing the collected responses. However, using a sample to determine the social behaviour of a specific population on a matter, often introduces errors that could affect the final outcome.

One of the main concerns when making web-based surveys comprises the introduction of biases in the received responses. Biases and limitations are highly dependent on the type of the survey and the sample size used to examine a social or scientific phenomenon with the scope of generalising the outcome (Couper, 2000). A relatively small sample might introduce reliability issues and biases due to possible variability among the received responses. Depending on the investigated phenomenon, small samples might not provide findings able to extrapolate to a generalised outcome, resulting to invalid conclusions (Faber and Fonseca, 2014). Addressing this issue might be challenging and although there are correction techniques for getting a valid estimation of what would be the research outcome in terms of the target population such as 'weighting adjustment', the survey design plays a significant role (Khan, 2019).

Two of the most frequent biases that could be introduced from a web-based survey consist of phenomena named under-coverage and self-selection (Bethlehem, 2010). Under-coverage bias occurs when only a part of the survey's target population can participate in the survey. This is a well-known phenomenon observed in web-based surveys, and poses bias in the final outcome as the survey applies only to a part of a population having Internet access. To assess the probability of under-coverage bias in this study, the percentage of people having Internet access in Denmark as well as the participation of the Danish population in social networks for private purposes were analysed. To assess the bias introduced due to the under-coverage phenomenon, the following formulas were used (Bethlehem, 2010):

$$\bar{Y} = \frac{1}{N} \sum_{k=1}^{N} Y_k \tag{3.2.1}$$

$$\bar{Y}_I = \frac{1}{N_I} \sum_{k=1}^{N} I_k Y_k \tag{3.2.2}$$

$$B = \bar{Y}_I - \bar{Y} \tag{3.2.3}$$

where the target population consist of $N$ elements, $Y_k$ is the target variable of the $k$ elements who have a driving licence, $N_I$ represents the number of individuals participating in social networks, and $I_k$ consists of a binary variable indicating if the element $k$ has (equals to 1) or does not have social media access (equals to 0). Eq. 3.2.3 consists of the bias ($B$) estimator. Due to lack of data for each k element concerning the relationship between driving licence and social network access, aggregated data of the entire Danish population were taken into account. According to Statista (2017) and 'Denmark Statistics', the percentage of the population having driving licence is approximately 89%, while the population having Internet access and presenting social media activity reaches 93% and 81% respectively (Statista, 2017; Statistics Denmark, 2019a, 2019b). It can be then assumed that most people in Denmark using social media, are licenced to use a private vehicle and therefore non-coverage bias could be assumed negligible.

Self-selection bias stems from the fact that the respondents of a web-based survey select themselves to participate or not in a survey. In this way, people having Internet access choose to participate in the survey eliminating the advantages of the probability theory application towards an unbiased result (Bethlehem, 2010). For coping with the self-selection bias, the survey's data gathered in this study were adjusted using the post-stratification weighting method. According to Loosveldt and Sonck (2008), post-stratification method is not always appropriate for solving self-selection biases due to an insufficient strong relationship between some variables and the demographic weighting variables used in this method (Loosveldt and Sonck, 2008). Based on Bethlehem (2010) the most reliable weighting technique for addressing self-selection bias is the propensity weighting where a variable is modelled to indicate whether or not someone participates in a survey. This method necessitates the use of a reference survey not conducted via the Internet in order to estimate the probability of each respondent participating in the Internet survey (Bethlehem, 2010). However, this study compiled in Denmark where it is documented that the probability of participating in online surveys presents a significant increasing tendency through the last years (Engmann, 2020) and to this end, it is assumed that the proportionality correction through the post-stratification weighting method could reduce the introduced self-selection bias adequately. The estimation of the adjustment weights used in the post-stratification method in this study was based on the following Eq. (Bethlehem, 2010):

$$w_k = \frac{N_h/N_b}{n_h/n} \tag{3.2.4}$$

where $w_k$ is the weight for an element $k$, $N_b$ is the target population size (people having driving licence by gender and age), $N_h$ represents the target population size in the stratum $h$ indicating the number of categories of the used variable (e.g. age group) during the post-stratification method, and likewise $n$ and $n_h$ represent the respective factors in the survey's sample. Due to lack of information regarding the number of people in Denmark who own a driving licence by gender, it has been assumed that the percentage of the Danish population by age and gender owing a driving licence is approximately equal to the one found in a western European country with similar social and economic characteristics (e.g. UK) (UK gov, 2020).

The census data used in computing the post-stratification weighting method and the calculated weights (through Eq. 3.2.4) for adjusting the received responses are presented in Table A2 (Appendix A2) (DTU Transport, 2015; Statista, 2017; Statistics Denmark, 2019a).The survey included both quantitative- and qualitative-oriented questions based on the stated hypotheses to assess the public's attitudes towards hydrogen technologies in transportation. The distributed survey consisted of 13 questions, seven of which were quantitative with closed responses to select from, and six of which were qualitative in order to identify the reasons and opinions about the willingness to purchase a hydrogen-powered vehicle as well as the prospects of the respective market (see Appendix A1). Additionally, an accompanied concise text divided in two parts was included in the questionnaire, informing the participants firstly of the main specifications of a contemporary FCEV and secondly on the economic perspectives of this technology.

The developed survey was divided into two main sections. The first section included the investigation of H2, H2.1, H4 and H2.2, and taking into account their assessment, H1 was also introduced to appraise the consumers' willingness to the hydrogen vehicle market. The second section included the investigation of H3, H3.1, H3.2, H4 and H4.1, also considering the results of the previous section. Based on the outcome of the second section, the prospects of the FCEV market in Denmark were evaluated.

According to the general model presented in Fig. 3.2.3, the stated hypotheses and the developed questionnaire, the identified variables affecting either directly or indirectly the PU and PEOU were assumed 2 and 10 respectively. The factors assumed to influence the prospects of the FCEV market through the stated hypotheses have been identified to five. Fig. 3.2.4 shows the theoretical developed model showing the respective factors and how these are assumed to be related to each other based on general model the stated hypotheses.

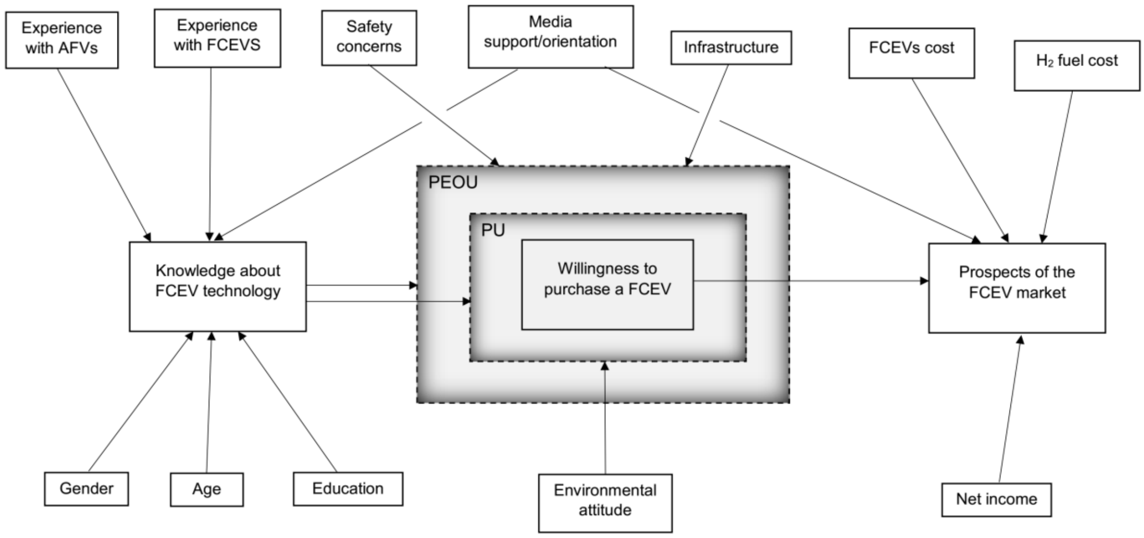



Fig. 3.2.4. Theoretical model to examine the stated hypotheses.

Based on Fig. 3.2.4 the proposed theoretical model is divided in two stages. The first part comprised the investigation of the willingness of the public to purchase a FCEV and was described as the top of a ‘pyramid’ built on the basis of PEOU and PU. The second part of the analysis assessed how the willingness of the public to purchase a FCEV based on the PEOU and PU in conjunction with the relative to this technology economic factors would affect the future prospects of the FCEV market in Denmark.

This mean that one may have the willingness to purchase a FCEV based on his/her PEOU and PU, but the economic factors such as vehicles’ capital cost and fuel prices may hinder the market expansion.

To test the theoretical model presented in Fig. 3.2.4, a SEM through path analysis was employed in IBM SPSS AMOS software. The overall assessment of the goodness of fit of the model was based on the p-value, the CFI and the RMSEA indicators, which according to (Suhr, 2006) and (Globisch et al., 2018) need to present values greater than 0.05 and 0.9 and lower than 0.08 respectively to indicate an acceptable fit.

The responses received from the survey participants were then introduced to the IBM SPSS statistics software tool, where a series of chi-square crosstab analyses of the participants’ responses were performed based on the final model to find if there is a significant effect between the variables under investigation. The effect between the investigated variables was assessed using Pearson’s chi-square asymptotic test given that none of the required assumptions were violated (i.e. large sample size, no sparse and unbalanced data). Otherwise, Fisher's exact test or the Monte Carlo simulation method for Pearson's chi-square test were taken into consideration, depending on the size of the dataset, which could impose intensive computing requirements (Mehta and Patel, 2012). The final assessment of the prospects for hydrogen mobility in Denmark seen from a social perspective identified the interactions between the research variables and the confirmation or rejection of the stated hypotheses.

### 3.2.4 Results and discussion

For this study, a total number of 158 people participated in the survey, including 61.5% male and 38.5% female, while the age groups were widely spread between '18+' and '74'. The education levels of the participants were as follows: 36% had a university degree, 35.4% a secondary education and 28.6% had other education levels. Most of the participants (78.3%) indicated a net annual income below 500,000 DKK (≈ €67,000), but only 33.3% of these declared a low annual income of less than 200,000 DKK (≈ €26,800). The detailed results of the study are documented in the appendices.

#### 3.2.4.1 Fit of the model

The results of the SEM application to the theoretical model presented in Fig. 3.2.4 (see Table 3.2.1) suggested a poor fit indicating the necessity to modify the model. Although the RMSEA was calculated to be within the range of a good model fitting, the other indicators were not in the acceptable range. Following the modification indices, all the indicators presented an acceptable value and the final model is presented in Fig. 3.2.5. The continuous bold lines are the ones derived from the theoretical model and the dashed bold ones indicate the effect lines based on the modification indices. The thin dashed lines indicate the identified by the SEM path analysis covariance between the investigated factors to secure the best fit of the model.

Table 3.2.1. Indicators showing the fit of the model.

| | p-value | CFI | RMSEA |
|---|---|---|---|
| Acceptable fit | < 0.05 | > 0.90 | < 0.08 |
| Theoretical model | <0.001 | 0.687 | 0.079 |
| Final model | 0.099 | 0.934 | 0.037 |

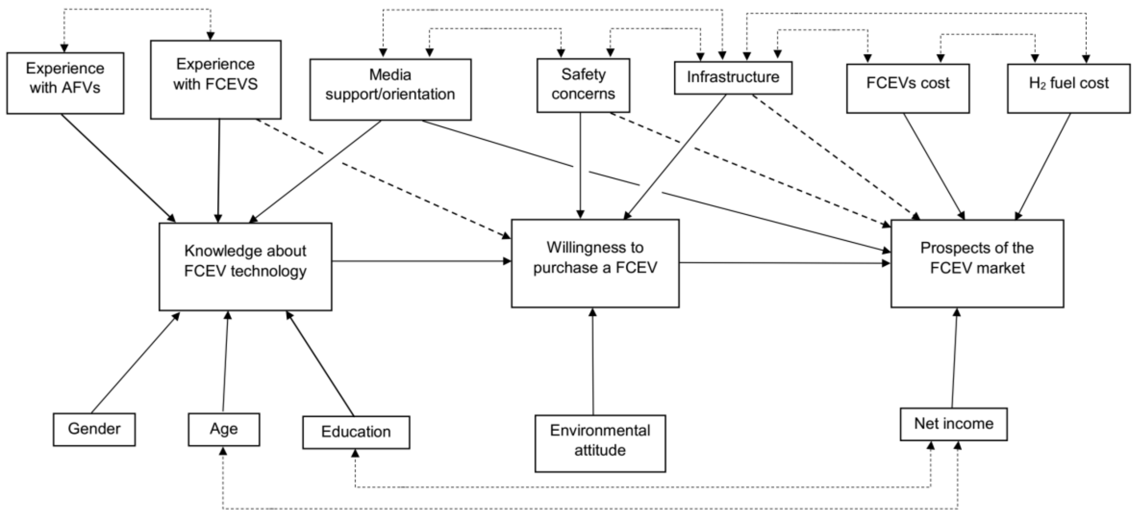



Fig. 3.2.5. Final model based on the theoretical model and the application of the SEM fitting assessment. Continuous line arrows: Identified factors from the theoretical model and confirmed by the SEM assessment. Bold dashed line arrows: Identified correlations between the factors by the SEM assessment. Thin dashed line arrows: Identified covariances between the factors by the SEM assessment.

By comparing the theoretical model presented in Fig. 3.2.4 and the final model as derived after the fitting assessment (Fig. 3.2.5), it is apparent that three more relations including 'previous experience with FCEVs → willingness to purchase a FCEV', 'safety concerns → prospects of the FCEV market' and 'infrastructure → prospects of the FCEV market' were identified to be crucial for the best fit of the model. It is apparent that these correlations seem logical as from an individual's perspective, on the one hand, prior experience with FCEVs would affect the PEOU and consequently the willingness to purchase a FCEV and on the other safety and infrastructure apart from the decision to purchase a FCEV will play a significant role in the future prospects of the FCEV market too.

In the next section of this research, the correlations and identified covariance between the factors participating in the model were analysed.

### 3.2.4.2 Knowledge of the hydrogen vehicle technology

The level of knowledge regarding hydrogen technology for transportation is assumed to play a significant role in the public's acceptance of the under investigation vehicles. This variable was studied in the context of six variables as showed in Fig. 3.2.5. The chi-square crosstab tests (see Appendix B1) revealed that due to the unbalanced data retrieved from the participants' responses, only the 'Gender' variable was assessed by Pearson's chi-square asymptotic test, while the other factors were analysed by either Fisher's exact test or the Monte Carlo method. Table 3.2.2 shows the significance results from the statistics test to determine the interaction between the respective variables and knowledge of hydrogen vehicle technology. In case of a significance below the .05 level, Cramer's V association measure is documented.

Table 3.2.2. Significance levels and Cramer's V results of the variables interaction with hydrogen vehicle technology knowledge.

| **Variable** | **Asymptotic significance** | **Exact significance** | **Monte Carlo significance** | **Cramer's V association measure** |
|---|---|---|---|---|
| Gender | 0.023* | N/A | N/A | 0.275 |
| Age | N/A | N/A | 0.619 | N/A |
| Education level | N/A | N/A | 0.685 | N/A |
| AFV experience | N/A | 0.007* | N/A | 0.271 |
| FCEV experience | N/A | N/A | < 0.001* | 0.366 |
| Media support | N/A | N/A | 0.007* | 0.245 |

*Significance at the 0.05 level (2-sided)

Based on the results presented in Table 3.2.2 and the respective data found in Appendix B1, it can be derived that 'Age' and 'Education level' of the survey participants do not significantly affect technology knowledge parameter (see Tables B1.2.2 and B1.3.2, respectively). On the contrary, 'Gender', experience with AFVs and FCEVs and 'Media support' presented a significant effect on the .05 level.

With regards to the 'Gender' factor results documented in Appendix B1.1, a significant percentage of female respondents declared lack of knowledge of this technology compared to the male counterparts, who presented higher percentages at the intermediate and higher levels of technology knowledge.

Prior experience of AFVs by either owning an AFV or knowing someone in the innermost circle of the participants owning an AFV (Appendix B1.4) contributed to the participants' level of knowledge above the average. Most of the responses received (107) indicated no prior experience of AFVs, of which 66% had little or no knowledge of hydrogen vehicle technology (see Fig. B1.4). Likewise, participants who either own, use or know someone owning or using a FCEV declared knowledge of these vehicles above average (Appendix B1.5). What is important to mention, however, is that a significant number of respondents who, although stated that they had no experience with this technology, they had a low to intermediate level of knowledge of FCEV technology (see Fig. B1.5).

The 'Media support' variable results (Appendix B1.6) showed a high significant effect on the technology knowledge of the participants. Specifically, based on Tables B1.6.1 and B1.6.2, there is a significant number of people who have no knowledge of FCEV technology and who have not noticed any support of the FCEV market from the media over the past year. Participants who declared a low to intermediate level of knowledge had noted media support of FCEVs between one and five times (see Fig. B1.6). On the other hand, media support ‘more than 5 times’ presented a significant effect on people who declared an intermediate to high level knowledge of FCEV technology.

The Cramer’s V association measure indicated that the factor with the most significant effect on the participants’ technology knowledge was prior experience with a FCEV followed by gender and AFV experience.

#### 3.2.4.3 Willingness to purchase a fuel cell electric vehicle

One of the crucial objectives of this research was to identify the opinion of the general public about FCEVs and its willingness to support this vehicle market based on the technology knowledge and the individuals’ environmental consciousness. To investigate this objective, the questions that the survey participants were asked to answer aimed at identifying the interaction of the factors assumed to affect their attitude towards FCEVs, including environmental awareness, knowledge and experience of the hydrogen vehicle technology, refuelling infrastructure and safety concerns. Table 3.3.3 includes the significance results of the statistical analyses between the above variables and the survey responses regarding the willingness of the participants to purchase a FCEV. The chi-square crosstab tests (Appendix B2) again showed that all factors data were unbalanced and thus the method used was Fisher’s exact significance test.

Table 3.2.3. Significance levels and Cramer’s V association measure results of the variables interaction with individuals’ willingness to purchase a FCEV.

| Variable | Exact significance | Cramer’s V association measure |
|---|---|---|
| Knowledge of FCEV technology | 0.022* | 0.235 |
| Individual’s environmental attitude | 0.019* | 0.222 |
| Refuelling infrastructure | 0.006* | 0.241 |
| FCEV experience | 0.005* | 0.242 |
| Safety concerns | 0.038* | 0.206 |

*Significance at the 0.05 level (2-sided)

The results of the significance levels of the above variables on the respondents’ willingness to purchase a FCEV showed that knowledge of the FCEV technology seems to have a significant effect towards the willingness of the individual to purchase a FCEV. Another factor that is considered important for the decision to invest in hydrogen transportation is the level of safety of the vehicles. The survey responses (Appendix B2.4) indicated that most of the respondents believe that FCEVs are as safe as conventional vehicles, and thus the statistical analysis showed that the positive opinion of the public concerning the safety of this technology is enhancing the willingness of an individual to purchase a FCEV and vice versa.

The interaction of the hydrogen vehicle technology awareness with the willingness to purchase a FCEV was found to be significant at the .05 level, and the analysis results (Appendix B2.1) suggested that the respondents who consider purchasing a FCEV have a level of knowledge of the specific technology above average, while the respondents who seemed unwilling to adopt this vehicle technology either declared absence or a low to intermediate level of knowledge of FCEV technology (see Fig. B2.1).

The public's willingness to purchase a FCEV is also affected by the individual's environmental attitude. The interaction between the eco-behaviour of the respondents and their acceptance of the hydrogen vehicle market presented a level of significance of $p < 0.05$, indicating high interaction between the two variables. Specifically, the statistical analysis found in Appendix B2.2 showed that the participants who are either willing to purchase or consider purchasing a FCEV characterise themselves as environmental friendly. A significant number of eco-friendly attitude responses indicated that they are unwilling to purchase a FCEV, whereas, not surprisingly, responses declaring no environmental awareness are correlated with the unwillingness to support this vehicle technology (see Fig. B2.2).

Prior experience with FCEVs has been identified to have a direct significant effect with $p = 0.005$ (Appendix B2.3). Although the total number of the participants who were positive about purchasing a FCEV was lower than the undecided or negative ones, it seemed that people who had prior experience with FCEVs were more willing to use this vehicle alternative. The respondents reluctant to purchase a FCEV did not seem to be significantly affected, regardless the level of experience (see Table B2.3.1).

A significant factor presenting a significant effect on the public's propensity to purchase a FCEV is the hydrogen refuelling infrastructure. Due to the limited number of publicly open HRSs, the PEOU of the public in Denmark seems to be negatively affected suggesting a hesitation towards the purchase of a FCEV. Based on the results presented in Fig. B2.5, the individuals answered that they are willing to purchase a FCEV believe too that the infrastructure needs to be enhanced.

The Cramer's V association measures showed almost the same significance effect for the infrastructure and the FCEV experience factors influencing one's propensity to purchase a FCEV with a slightly higher effect caused by the knowledge level of the hydrogen vehicle technology followed by the individual's environmental attitude and safety concerns.

### 3.2.4.4 Prospects of the fuel cell electric vehicles market

The prospects of the commercialised hydrogen technology in the automotive sector are assumed to depend on seven different factors (see Fig. 3.2.5). These include, apart from the individual's willingness to purchase a FCEV based on environmental and technology awareness, economic factors, safety concerns, media support, and the refuelling infrastructure status. Similarly to the previous tests, the chi-square crosstab statistical test (Appendix B3) showed a sparse distribution of the respondents' answers, resulting in the use of Fisher's exact test and the Monte Carlo method. The significance level results along with the Cramer's V measures are presented in Table 3.2.4.

Table 3.2.4. Significance levels and Cramer's V results of the variables identified to influence the prospects of the hydrogen vehicle market.

| Variable | Exact significance | Monte Carlo significance | Cramer's V association measure |
|---|---|---|---|
| Willingness to purchase a FCEV | <0.001* | N/A | 0.381 |
| FCEV price | 0.028* | N/A | 0.205 |
| Hydrogen fuel price | 0.331 | N/A | N/A |
| Individual's net income | N/A | 0.150 | N/A |
| Refuelling infrastructure | 0.009* | N/A | 0.227 |
| Safety concerns | 0.030* | N/A | 0.203 |
| Media orientation | N/A | <0.001* | 0.347 |
| Future FCEV price | <0.001* | N/A | 0.313 |
| Future hydrogen fuel price | N/A | 0.002* | 0.271 |

*Significance at the 0.05 level (2-sided)

The test results indicated that the current hydrogen fuel prices and the respondents' net income in Denmark have no significant impact on the hydrogen vehicles market (Tables B3.4.2, B3.3.2). In contrast, the current cost of a FCEV was deemed by most of the survey respondents (i.e. 134) to be high suggesting a significant effect between the FCEV price and the prospects of the FCEV market interaction (Table B3.2.2). Based on Table B3.2.1 and Fig. B3.2, most of the participants believe that with the current price of FCEVs, the FCEV market will be hindered as their responses revealed a tendency showing a lack of interest in purchasing a FCEV in the near future. On the other hand, although most of the participants declared that current refuelling cost of FCEVs needs to decrease further, the current cost was found not to significantly affect the prospects of the future FCEV market.

Many experts and other survey results find that the hydrogen refuelling infrastructure is one of the main drawbacks in the development of a robust FCEV market (Apostolou and Xydis, 2019; Hardman et al., 2017, 2016; Iribarren et al., 2016). In the context of this study, most of the respondents (see Fig. B3.5) agreed that the hydrogen refuelling network needs to be enhanced, and similarly to other studies, the results indicated that infrastructure presents a significant effect on the future prospects of the FCEV market indicating that the current state of refuelling infrastructure consists of a barrier that needs to be eliminated.

The interaction between the willingness to purchase a FCEV and the prospects of a hydrogen transportation market showed a high significant effect that can be interpreted by using the respective tables in Appendix B3.1. Specifically, it is apparent that respondents who are positive or consider purchasing a FCEV believe that in the next years, it may be highly possible to adopt this vehicle technology contributing to a development of the market. It is also interesting to note that a number of the survey participants who are reluctant to purchase a FCEV based on their environmental attitude and technology knowledge seemed to identify themselves as potential future users of the hydrogen vehicle technology (see Fig. B3.1). In fact, more than half of the participants did not reject the idea of purchasing a FCEV in the near future, while only 6% of the total participants were completely against this type of technology.

Another factor that was assessed to significantly affect the future prospects of the FCEV market as documented by the survey's participants comprised the safety concerns around the hydrogen transport technology. A large percentage (≈ 64%) of the participants stating that FCEV technology is as safe as normal petrol vehicles or even safer suggested that they are going to invest in a FCEV in the near future (see Table B3.6.1 and Fig. B3.6).

The media's contribution to the prospects of a competitive FCEV market was assessed to be significant with a significance level of $p < 0.001$. The results indicated that participants who believe that the media should focus more on the FCEV market are positive about purchasing a FCEV, and others who have a neutral or negative opinion about the media's future support seem to be reluctant to a FCEV market (Appendix B3.7).

Although the final model did not include the future reduction potential of the capital and fuel costs of FCEVs as forecasted by several studies (Apostolou and Xydis, 2019) due to resulting in poor model fitting, the survey participants were asked about their opinion about how a future decrease of the cost of this transport technology could affect a future potential FCEV market. The analysis outcome indicated that a future reduction of the FCEV price by 50% was perceived by 86% of the respondents as a catalytic factor for market competitiveness (Appendix B3.8). A FCEV price reduction will have a significant effect on people considering purchasing a FCEV as their next vehicle and among those likely to invest in a FCEV in the years to come. In the context of a future decreased hydrogen fuel cost, the survey results showed an interaction significance for the participants who consider purchasing a FCEV in the near future as well as those negative to this market (Appendix B3.9), which was however in contrast to the current fuel cost factor.

The assessment of the significance level through Cramer's V test showed that the willingness of the participants to purchase a FCEV is the most important factor affecting the market prospects, followed by the media orientation, and the infrastructure enhancement.

#### 3.2.4.5 Covariance analysis between the investigated factors

The final model that the analysis was based on, presents the covariance between the factors affecting the investigated variables (see Fig. 3.2.5). The covariance results indicating the relationships between the covariates are presented in Table 3.2.5.

Table 3.2.5. Covariance between the factors identified in the final model.

| Variables | Covariance |
|---|---|
| Age ↔ Net income | 0.877 |
| Education level ↔ Net income | 0.280 |
| AFV experience ↔ FCEV experience | 0.088 |
| Media support ↔ Safety concerns | 0.021 |
| Media support ↔ Infrastructure | 0.080 |
| Safety concerns ↔ Infrastructure | 0.059 |
| FCEV price ↔ Hydrogen fuel price | 0.266 |
| FCEV price ↔ Infrastructure | 0.168 |
| Hydrogen fuel price ↔ Infrastructure | 0.195 |

The covariance values presented in Table 3.2.5 show a positive interaction between the connected factors. Both age and education level of the participants covariance with income indicates a positive relation as it was expected. FCEV and AFV experience covariance indicate that individuals having some short of experience with FCEVs might have experience with AFVs and vice versa. Media support with safety concerns and infrastructure also present a positive covariance showing that as media support increases, safety and infrastructure status acknowledgment would increase and vice versa. Likewise, when individuals acquire knowledge about hydrogen infrastructure status, they would increase their knowledge on safety issues regarding the FCEV technology. On the opposite side, as safety concerns are addressed, infrastructure enhancement would be more supported by the public.

From a financial point of view, the capital cost of a FCEV with the hydrogen fuel cost has a positive covariance showing that it is more likely that as the cost of the vehicle would drop resulting to a higher potential of the market, so the fuel cost could be reduced and vice versa following the law of demand where reduced prices of a product increase the demand. In the same context, an increase of the HRSs number would decrease the hydrogen fuel cost.

### 3.2.5 Main outcome

The statistical analysis of the received responses from a survey, which intended to assess the public opinion about the hydrogen-fuelled private transportation sector, revealed the factors affecting the prospects of the FCEVs market as well as the steps needed to be taken to support the efforts towards 'green' mobility configurations. The novelty of this study can be described in three main aspects:

1) The developed methodology can be applied to any sustainable technology for all means of transportation and in different countries to assess the market prospects.

2) The current study analysed not only the benefits and drawbacks of this technology to society but also investigated the interactions of these factors with the prospects of the FCEV market.

3) The results indicate the sectors that authorities and relative businesses should focus on to enhance the FCEV market.

The results aimed to identify the validity of the stated hypotheses, set accordingly to assess the status and future prospects of the hydrogen vehicle market as perceived by the public. The Danish public has been found to be environmentally sensitive (≈75%), and their attitude towards a direct emission-free transportation technology such as hydrogen is significantly affected by this. So, based on the results, hypothesis H1 is confirmed. Knowledge of the technology also has been proved to have a significant positive or negative influence on individuals' willingness to invest in FCEVs (i.e. hypothesis H2). However, hypothesis H2.1 can only be partially confirmed because although prior experience with FCEVs seems to have a direct and indirect effect (i.e. through technology knowledge) on consumers' incentive to purchase a FCEV, AFV experience showed only an indirect effect through technology awareness. Hypothesis H2.2 is also rejected, as more than 85% of the Danish respondents believe that FCEV technology is at least as safe as conventional vehicles and thus safety concerns about hydrogen mobility in Denmark seems not to be a barrier to the propensity of the public to purchase a FCEV.

Hypothesis H3 is rejected by the respondents, because although 78.3% of them believe that the refuelling cost of FCEVs needs to be reduced, the fact that current cost is comparable to the one of conventional fuels introduced no significant effect on the prospects of the FCEV market. Hypothesis H3.1 is confirmed as the significance level was found to be <0.05. So, most of the survey participants believe that the current FCEV price is high, suggesting an important factor for their decision to purchase a FCEV in the near future. In this context, it could be argued that according to current fuel cost results presented in Tables B3.3.1 and B3.3.2, the fuel cost level is considered not capable to significantly affect their propensity to invest in FCEVs in the future. Therefore, the answers concerning the future reduction of the refuelling cost (i.e. part of H3.2) cannot be considered capable to provide a robust outcome as compared to the aforementioned analysis there is a contradiction. The explanation behind the respondents in regards to the refuelling cost part of H3.2 could comprise the fact that a price reduction is always appealing for the consumers suggesting a bias towards the support of the FCEV market under an assumed reduction of the respective refuelling prices.

The media support (hypothesis H4) on the hydrogen alternative vehicle was assessed from the perspectives of technology awareness and the prospects of the respective FCEV market. In both cases, the statistic results of the empirical study showed a significant effect. The outcome showed, on the one hand, that media orientation plays a significant role in enhancing the public's knowledge about the benefits or drawbacks of the technology, and, on the other hand, that future media support would favour the FCEV market. The refuelling infrastructure status (hypothesis H4.1) was assessed by the participants to be inadequate posing a significant effect on the prospects of the FCEVs market, which, based on the Danish public's opinion, indicates that the sparse hydrogen refuelling network must be developed in order to support a future FCEV market.

Among all the identified factors that significantly affect the expansion of the FCEVs market, some were found to present a higher level of influence. Based on Cramer's V association measure, it can be derived that the prospects of the FCEV market are highly affected by the participants' willingness to purchase a FCEV as well as the media orientation to support this type of technology. Subsequently, the willingness to purchase a FCEV is influenced by the level of technology awareness, which is also affected by the media support, the prior experience with this type of technology, and the environmental sensitivity of the public. Therefore, one may support that the main obstacle identified to hinder the development of the FCEV market in Denmark is on one hand the limited PEOU of this technology, the lack of media support and the low number of refuelling infrastructure.

### 3.2.6 Conclusions

This research identified the factors that could influence the public acceptance of hydrogen-powered vehicles and examined their effect on the prospects of a hydrogen mobility through a set of hypotheses. Data were collected through an online survey in which 158 respondents participated. Initially, an identification of possible introduced biases was assessed and correction factors were applied in order to be able to generalise the outcome to the Danish target population consisting of the individuals with a driving licence and therefore potential consumers in the vehicle market. The answers were then analysed with crosstab statistical tests, and the results showed that most of the hypotheses could be confirmed. These included, among other things, the environmental attitude of individuals, the refuelling price of hydrogen, the capital cost of hydrogen vehicles as well as the effects of media orientation following increased information and advertising in Denmark. These factors can be said to affect one's willingness to accept or even purchase a FCEV in the near future. However, it is necessary to highlight that this study concerns the Danish public and cannot be generalised to the global vehicle market. Obviously, some of the analysed results such as media support or even technology awareness probably have the same effect in other EU countries, while it can be assumed that factors associated with other countries' economic status may impose different results. Future research could use this methodology by incorporating an EU-scale survey on FCEV prospects to assess the social acceptance of hydrogen as a transportation fuel as well as the reason why the FCEV market in Europe is significantly hindered compared to the respective ones in the US and Japan. Hence, the methodology followed in this research can be applied in other countries too by altering social and economic input factors such as the population's income, environmental awareness and vehicle market accessibility in order to identify the potential of hydrogen mobility. Another benefit of the presented methodology is the elasticity it offers for identifying the prospects of alternative vehicle technologies too by adjusting the inputs concerning the specifications of the under investigation technology (e.g. infrastructure, fuel cost, vehicle capital cost, etc.).

However, it should be noted that extra caution is essential during the survey development in order to eliminate errors occurring during population sample analyses. Although the post-stratification weighting method used in this study could be deemed to have adequately reduced the introduced biases, absolute elimination of the inherent biases stemmed from web-based surveys cannot be fully neglected. To this end, a further investigation of these factors would provide more robust results by introducing a larger sample of respondents in conjunction with survey mixed methods including in addition to online surveys, either personal interviews or/and questionnaire targeted distribution, aiming to get as much unbiased results as possible.

# 4. Why and how a green hydrogen production system participating in wind power and electricity markets could be a viable solution towards sustainable light-duty transportation?

The second RQ aimed to present the benefits of a coupled WH system connected either with the electricity network or as an autonomous system in the context of transport applications. The participation of a hydrogen system in both the wind and electricity markets was deemed crucial for the assessment of the development of a network of HRSs for urban hydrogen mobility. The two journal articles addressing the above-mentioned issues are:

- D. Apostolou, P. Enevoldsen (2019). The past, present and potential of hydrogen as a multifunctional storage application for wind power. *Renewable and Sustainable Energy Reviews*, 112, pp. 917-929, https://doi.org/10.1016/ j.rser.2019.06.049.

- D. Apostolou (2020). Optimisation of a hydrogen production – storage – re-powering system participating in electricity and transportation markets. A case study for Denmark. *Applied Energy*, 265, 114800, https://doi.org/10.1016/j.apenergy.2020.114800.

## 4.1 The past, present and potential of hydrogen as a multifunctional storage application for wind power

Contemporary electrical networks are moving towards distributed electricity production via the implementation of renewable energy sources. One of the most developed renewable technologies comprises the transformation of the wind's kinetic energy to electrical energy by using wind power converters. However, wind power production is highly dependent on the weather conditions and specifically the available wind resource of an area. Intermittent electricity production of wind turbines hinders their further integration in electricity networks suggesting among other solutions, the implementation of energy storage configurations in order to cope with their stochastic operation.

Based on an extensive literature review, this study reveals the potential future role of hydrogen as a multifunctional storage application for wind power. The analyses are carried out to identify the focus of recent studies on coupled wind and hydrogen systems in order to define the potential of such systems and predict the future collaboration between the two technologies. Based on the results, it can be derived that research on wind-hydrogen systems is shifting focus from solely applying hydrogen as a storage application to exporting hydrogen as a bi-product to improve wind power investments. Furthermore, the outcome shows that there is an increasing interest in using wind power generation to produce hydrogen as an end product designed specifically for transportation purposes, while contributing simultaneously to a more sustainable energy mix. This paper provides an ultimate overview of wind-hydrogen systems, which reveals the development as well as the state-of-art of such system's applicability in connection to its changing efficiency.

### 4.1.1 Introduction

The use of storage technologies in conjunction with wind power is a major topic in the energy research community, since wind power is projected as the most important energy source in various 2050 scenarios (Jacobson et al., 2017; Söderholm et al., 2011) with already approximately 540 GW installed ultimo 2017. Nevertheless, wind power is inherently an intermittent source, and one method for achieving its higher integration in the electrical systems is the use of storage (Bernal-Agustín and Dufo-López, 2008; Mohammadi and Mehrpooya, 2018; Schroeder, 2011) and/or super grids (Xydis, 2013a). The storage required for wind power is especially focused on the connection between various grids, peak shaving and load shifting from continuous demand fluctuations (Luo et al., 2015). For these purposes, EES has been identified as the most promising method to store electrical energy (Luo et al., 2015). The methods applied can overall be divided into four main categories, namely chemical, thermal, mechanical and electrical storage (Díaz-González et al., 2012; Luo et al., 2015), and the innovations and research studies stretch from the first installed PHS facility in 1929 (Chen et al., 2009) to research on storage through molecular solar thermal systems in 2018 (Kilde et al., 2018).

Despite the increasing academic focus, only a few operating industry scale storage facilities have been installed worldwide (Aneke and Wang, 2016). One issue might be the development of several storage technologies still lacking sufficient maturity, at least for the solutions applicable in a distributed format (Guney and Tepe, 2017), which is required due to the increasing planning demands forcing onshore wind turbines into various configurations and locations (Enevoldsen and Valentine, 2016). For distributed technologies, batteries are considered the most developed technology, and for many years, hydrogen in particular has been tested in multiple demonstration cases (Kourkoumpas et al., 2018). In fact, hydrogen testing has a long history that dates back to 1891 when the first known example of wind energy based hydrogen production occurred through a water electrolysis system powered by an electric generator connected to a windmill (Carton and Olabi, 2010).

Besides the requirement of applying distributed technologies, the environmental impact of storage technologies is also worth investigating. The environmental impact of manufacturing electrolysers and

FCs is low, and so is the impact during the operational phase as well as the actual decommission of the hardware (Guney and Tepe, 2017). Battery technologies have individual environmental impacts, yet, overall, most have toxic remains (Chen et al., 2009) and are depending on limited natural sources (Aneke and Wang, 2016).

In this context, many researchers focussed on the environmental benefits of electrolytic hydrogen coupled to RES compared to other production methods. In terms of LC emissions, wind-based electrolysis presents lower $CO_2$ emissions than other RES coupled systems reaching approximately 1 kg of $CO_2$ per 1 kg of produced hydrogen. In contrast, other methods of $H_2$ production such as coal gasification and steam reforming of NG emit much higher $CO_2$ quantities reaching up to 21.7 kg and 9 kg of $CO_2$ per 1 kg of produced hydrogen respectively (Bhandari et al., 2014; Burmistrz et al., 2016).

Additionally, another important aspect is the cost of the storage service, which is added to the energy-producing technology, in this case the wind turbine. The LCOE for various wind farm settings is below the median cost of conventional fuels as summarised by (Enevoldsen, 2018). This is further supported by Lazard (2017), who detected a minimum LCOE for wind at €26.4 per produced kWh, which is below any conventional fuel source (Lazard, 2017). The cost of EES technologies constantly changes, and in 2012, the cost of electrochemical capacitors ranged from 8,800 €/kWh for electrochemical capacitors to 8.8 €/kWh for CAES (Sundararagavan and Baker, 2012) to 4,400 €/kWh for flywheels to 1.8 €/kWh for CAES in 2016 (Aneke and Wang, 2016). The mature storage technology of PHS is most likely to be below 0.9 €/kWh (Aneke and Wang, 2016), while other sources incur costs as low as 0.02 €/kWh (Ferrero et al., 2016). Nonetheless, CAES and PHS have very specific geographical requirements, and furthermore, the costs do not take into account the additional land use challenges with the trend of modern farms being close to large urban areas (Enevoldsen et al., 2018). Instead, distributed technologies such as batteries and hydrogen solutions are preferable on a general basis. The lowest cost of batteries applied in projects range from 8.8 €/kWh for zinc-air batteries to 528 €/kWh for lithium-ion batteries (Aneke and Wang, 2016), and hydrogen plant costs for seasonal energy storage vary from 44 to 916 €/MWh depending on the technology used, which is considerably lower than other renewable energy storage technologies, except for PHS (Ferrero et al., 2016; Hydrogen Council, 2017a; van Leeuwen and Mulder, 2018).

Adding the cost of the storage technologies, while meanwhile accepting a loss in the roundtrip efficiency, the LCOE of wind power increases to a level above the cheapest conventional fuel sources. However, when considering the social cost of implementing 100% renewables, including the storage, a recent research determined the potential cost of a stable renewable energy supply to be one-fourth lower than that of conventional fuel (Jacobson et al., 2018). Therefore, it is important to apply investment strategies, which allow storage technologies to add value beyond stabilising the energy output from a wind power plant. Such studies have been carried out by Hou et al. (2017) and Enevoldsen et al. (2018), who both examined the opportunities to maximise profit from wind farms by storing and exporting electricity and hydrogen at strategic hours (Enevoldsen et al., 2018; Hou et al., 2017). Both studies concluded that a mix of electricity and hydrogen export would optimise the business case for onshore wind farms. The multiple purposes and income opportunities from hydrogen have previously been highlighted as an advantage (Guney and Tepe, 2017).

Based on the above, it has been decided to investigate the current state of hydrogen storage for wind turbines in order to provide insight into the recent decades' development, and, furthermore, to examine whether the present state of hydrogen storage can contribute as the storage application for modern wind farms towards a sustainable energy future. To this end, analyses of the data found in peer-reviewed literature in relation to WH systems have been performed in order to identify the state-of-art and possible drawbacks, which hinders the further development of this technology.

### 4.1.2 Methodology

In the investigation of hydrogen systems coupled with wind turbines, a range of studies used simulation tools and models to evaluate such hybrid arrangements (Enevoldsen and Sovacool, 2016; Hou et al., 2017; Kavadias et al., 2018; Samaniego et al., 2008; Sovacool and Hirsh, 2008), while others were based on experimental results coming from the implementation of pilot projects (Dutton et al., 2000; Kopp et al., 2017; Ulleberg et al., 2010; Varkaraki et al., 2006). In order to proceed with a detailed review of previous research studies focusing on WH hybrid systems, the authors followed a specific approach comprising three main steps (Onwuegbuzie, 2016). The first step was to find all relevant papers concerning RES coupled with hydrogen technologies. The next step was to select the studies focusing entirely on wind power coupled with hydrogen systems, and finally, the WH systems were grouped into three main areas of research. The three areas include 1) grid-connected systems for increasing the penetration of wind power in the electrical networks, grid stabilisation, balancing and re-electrification services via FCs; 2) simulated or pilot stand-alone systems for either experimental operation or for covering the electricity demand at autonomous grids through FCs; and 3) WH systems used for covering $H_2$ fuel demand in transportation. The research also focussed on the identification of LC assessment studies for WH systems in order to evaluate the environmental aspects of this technology in a lifetime perspective.

Specifically, the literature review resulted in 4,316 journal and conference articles published since 2000. The majority of the literature concentrated on hydrogen technologies coupled with other RES technologies such as photovoltaic or biomass, while other papers focused on hybrid wind-based RES systems or various non-renewable methods of $H_2$ production. In the second step, the aggregate number of papers identified was 51, of which 19 were within the first research area, 19 within the second, 5 within the third, 3 papers investigated more than one area, while 5 papers are identified to assess the LC environmental aspects of WH systems. Therefore, a filtering process was carried out to select only the papers focusing on wind turbines and hydrogen storage. The remaining papers stretched over 15 years and have been summarised in Fig. 4.1.1 below.

The search for literature furthermore revealed that over the past 20 years, there has been a high volume of scientific studies investigating the technical and economic feasibility of wind power-hydrogen systems. In this context, contemporary research on hydrogen focuses mainly on a three-axis perspective. Firstly, most studies examine hydrogen as an energy storage medium for increasing the penetration of wind power in the electrical networks while providing grid stabilisation and balancing services via FCs.

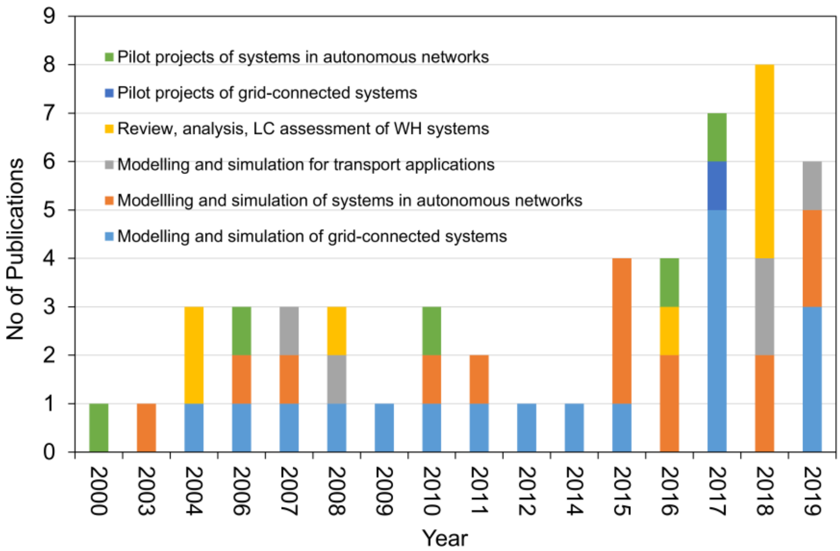


Fig. 4.1.1. Output from literature review.

Secondly, other research focuses on simulations or experimental studies on stand-alone systems, and thirdly, some examine the use of hydrogen gas as fuel for transportation (González et al., 2004; Kavadias et al., 2018). In addition to the above-mentioned perspectives, this study presents also papers and reports regarding the LC assessment of WH topologies and how the respective findings are compared to other conventional technologies. The methodological approach of this study is to consider all the perspectives in order to provide a holistic insight into hydrogen storage applications anno 2018.

### 4.1.3 Hydrogen as a multi-purpose collaborator for wind energy

Hydrogen energy storage systems consist of a production unit, usually a water electrolysis apparatus, a hydrogen storage configuration, other auxiliary components, such as compressors, piping and control, as well as safety systems and hydrogen utilisation equipment, such as FCs (see Fig. 4.1.2).

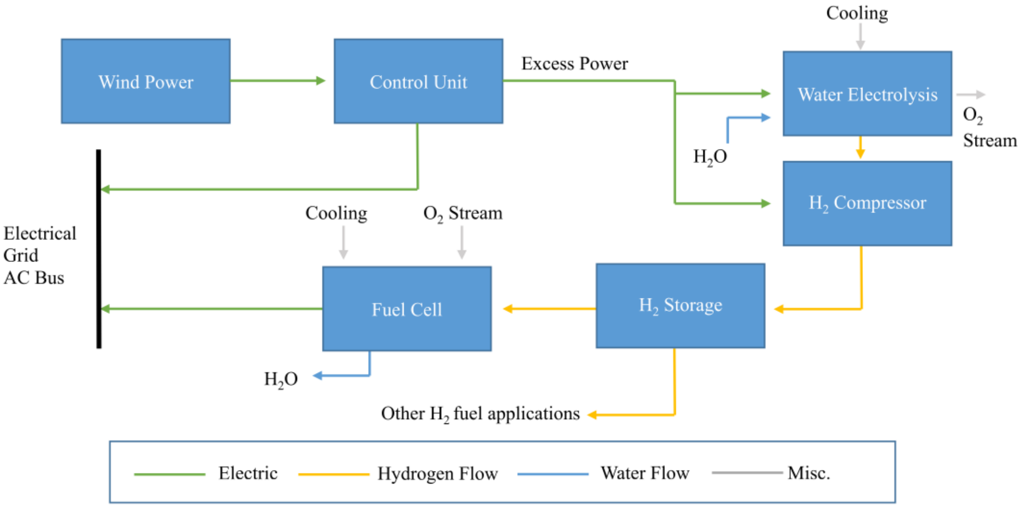



Fig. 4.1.2. Wind energy storage configuration based on hydrogen technologies.

Fig. 4.1.2 introduces and illustrates the configuration of a multi-purpose WH system, allowing for electricity outlet from the wind turbine, power-to-power using the electrolyser and the FC, and finally P2G by selling hydrogen instead of re-converting it to electric energy. Fig. 4.1.2 defines the possibilities of WH systems, which are further examined in the literature review in the following subsections.

#### 4.1.3.1 Grid-connected WH systems allowing high wind power penetration and providing ancillary services

WH systems are considered one of the most interesting technologies for coping with problems arising from the integration of wind energy in electrical networks. González et al. (2004) presented a simulation and optimisation study of a wind-powered hydrogen production system for increasing wind energy penetration in Ireland. The case study showed an electrolyser's efficiency between 79% and 87% based on HHV. The optimal case where excess wind produced energy drops to 7.5% of the initial surplus is a 30 MW electrolysis plant with an $H_2$ price of 30 €/GJ and a surplus electricity value of 2 c€/kWh. The authors investigated also the potential of wind-produced hydrogen in reducing emissions arising from both the transportation sector and the conventional electricity generation power plants. Specifically, installations of 5 GW of wind power in Ireland could refuel 541,422 FC electric vehicles resulting to avoided emissions of 1,693 kt/yr of $CO_2$, 4,500 t/yr of eq-$SO_2$ and 1,402 t/yr of $NO_x$, while the total $CO_2$

emissions avoidance from both electricity production and transportation has been calculated to approximately 10 Mt/yr (González et al., 2004). Similarly, Schenk et al. (2007) assessed a grid-connected WH storage system to increase wind penetration in the Netherlands. The authors concluded that integration of more than 8 GW of wind power in the network showed significant hydrogen production, resulting in an ancillary beneficial effect on the grid (Schenk et al., 2007). Moreover, García Clúa et al. (2011) analysed the operation of a grid-connected WH system for optimum wind capture and maximum hydrogen production. For operation of the system under optimum wind power capture, the electrolyser harnessed a fraction of the generated power, while the rest was injected to the grid. For operation at the rated power of the electrolyser, it was necessary to be connected to the grid because the energy production from wind was lower during most of the under investigation time (García Clúa et al., 2011).

A techno-economic analysis of a WH system for storing energy during off-peak hours and generate electricity by FCs during peak hours through hourly energy management has been published by Bernal-Agustín and Dufo-López (2008). Several examined scenarios showed that WH systems could follow the demand compared to a wind-only system. However, high capital costs and low efficiency of the electricity-hydrogen-electricity conversions (lower than 40%) result in high prices of electricity generated by the FC reaching 171 c€/kWh (Bernal-Agustín and Dufo-López, 2008). Aguado et al. (2009), on the other hand, developed a simulation model for financial assessment of WH energy systems compared to no-energy storage wind farms. The electrolyser used, demonstrated an efficiency range between 77% and 82% based on the input power. Three scenarios comprising 18 MW and 42 MW of wind power as well as 42 MW with $H_2$ production storage showed that although initial investment in scenario 3 is three times higher than the second case, curtailments are less, and the respective cost of electricity is higher (Aguado et al., 2009).

A techno-economic analysis of hydrogen production by wind energy in Turkey based on a 6 kW WT and a 2 kW PEM electrolyser was compiled by Gökçek (2010). The annual operation of the system revealed high variations of the hydrogen production, which is dependent on the season and the different hub heights investigated. By increasing the hub height from 12 m to 60 m, hydrogen production increased by 67%. The levelised cost of hydrogen decreased from 18.9 €/kg$H_2$ for 12 m hub height to 12.5 €/kg$H_2$ for 60 m hub height with a grid-independent system, while with a grid-connected system, the cost ranged between 0.13 €/kg$H_2$ and 3.98 €/kg$H_2$ based on the hub height of the WTs. Additionally, the author concluded that the annual production of wind-generated electricity equalled to 15,148 kWh, while the produced hydrogen mass to 102.4 kg (Gökçek, 2010). Based on the values of $CO_2$ emissions per kWh$_e$ per energy source presented by Kaldellis and Apostolou (2017), the corresponding $CO_2$ avoided emissions might range between 6,816 kg and 15,905 kg of $CO_2$. On the other hand, production of 102.4 kg of hydrogen might be used in the transportation sector as fuel for FC vehicles (Kaldellis and Apostolou, 2017).

Additionally, Genç et al. (2012) analysed the economics of a grid-connected WH system. The study examined different WTs at different hub heights, two PEM electrolyser configurations and a PEM FC to cover the demand of a farm in Turkey. The authors concluded that the electricity cost of the WTs and the cost of $H_2$ decreased by increasing the hub height (i.e. from 50 m to 100 m). The cost of $H_2$ also decreased by decreasing the rated power of the electrolysers. The $H_2$ cost ranged between 26.6 €/kg$H_2$ for a 0.8 MW WT and a 120 kW electrolyser, and 7.3 €/kg$H_2$ for a 3 MW WT and 3 x 40 kW electrolysers (Genç et al., 2012).

In relation to the WT, wind farm type and hydrogen supply network, Kim and Kim (2017) introduced an optimisation model to design and analyse a WH system based on decision variables, including technical selection of the WT, wind farm type (onshore or offshore) and hydrogen supply network development. The findings of this research indicated that the type of the WT and wind farm layout is dependent not only on the wind resource and hydrogen demand but also government regulations. Onshore installations showed lower capital costs and are preferable, although their energy yield is lower than offshore farms. A centralised electrolyser is more cost-efficient due to economies of scale, while the range of the levelised cost of hydrogen has been calculated between 7.8 €/kg$H_2$ and 11.5 €/kg$H_2$ (Kim and Kim, 2017).

Zhang and Wan (2014) developed a model for enhancing wind integration in the electrical network via a grid-connected hydrogen production system in Mongolia. In the specific region, curtailed wind energy reaches 103.2 GWh accounting to more than 28% of total wind-based electricity production. The authors proceeded to perform an economic evaluation of the WH system for different electrolysers. Through the comparison of two WH production scenarios, the research concluded that continuous operation of the electrolyser within a power range between 25% and 100% is more profitable. The $H_2$ price balance point has been found to be 0.25 €/$Nm^3$, which is lower than the direct costs when the electrolyser is supplied entirely by the electrical grid (0.36 €/$Nm^3$). An integration of a such WH configuration has been found to reduce wind curtailments down to 6.4 GWh suggesting integration of wind-produced electricity of approximately 97 $GWh_e$ in the electrical grid (Zhang and Wan, 2014).

An analysis of the potential of a grid-balancing system, including wind energy and P2G configurations based on hydrogen production from water electrolysis has been introduced by Guandalini et al. (2016). The authors concluded that from an economic and technical point of view, the P2G concept was not unfavourable compared to a conventional balancing system based on gas turbines. From the energy balance perspective, P2G lowers wind curtailments, though the efficiency of electrolysers confine the portion of the wind energy actually exploited (Guandalini et al., 2016). Under the same scope of securing a balanced electrical system, Grueger et al. (2017) investigated the potential to reduce wind farm forecast errors and the system's ability for secondary control reserve. The economic potential of marketing FCs and electrolyser systems is examined simultaneously. Through the presented analysis, the authors concluded that reducing wind farm forecast errors by 17% is accomplished at low capacity installations of electrolyser and FC (0.7 MW and 0.2 MW, respectively). To have an economically viable system, the FC required hydrogen fuel at a cost less than 1.25 €/kg$H_2$, while the operational cost of the electrolyser has been found to be between 2 €/kg$H_2$ and 3 €/kg$H_2$ (Grueger et al., 2017).

Guandalini et al. (2015) studied the case of a balancing system including a 620 MW electrolysis installation powered by wind power parks of 16 GW and coupled with a conventional gas turbine of 315 MW. This system is used to balance the integration of wind power in the electrical network, while inject the produced $H_2$ in the NG grid. On one hand, the injected $H_2$ in the NG grid substitutes a fraction of energy consumption and thus GHG emissions are reduced. On the other hand, based on a scenario where the electrolysis operates almost continuously, wind integration increases and the operating hours of the gas turbine decrease resulting to lower emissions. The authors calculated that the annual avoided emissions of such a system may reach 147 kt (Guandalini et al., 2015).

Alvarez-Mendoza et al. (2017) investigated a hybrid system consisting of a wind power electrolyser PEM FC in order to cope with wind power volatility. They developed a probabilistic information model for short-term wind power generation and electricity production from the hydrogen system. The results of this study showed that the connection of the system to the network did not destabilise the frequency and reduce the intermittence compared to other systems without the application of the developed model. When analysing different scenarios, the output of the system can be modified according to the load and the $H_2$ storage configuration (Alvarez-Mendoza et al., 2017).

The operation of the grid-connected pilot project 'Energiepark Mainz' in Germany has been analysed by Kopp et al. (2017). The system consists of an 8 MW wind farm and a water electrolysis system of 6 MW capacity. The results derived from the first two months of the project showed that the efficiency of the electrolyser decreased at higher loads (64% at a power input of 4 MW; 59% at rated power). The results of the economic analysis indicated that the most economical option for the P2G plant was the participation in the control reserve market. For initial experience, the project participated in the minute reserve market where the procured electricity for the P2G was low at 72.5 $MWh_{el}$, and due to capacity prices and high energy prices, the income was 4,052 €. In terms of price per $H_2$ mass produced, the total electricity costs were 0.85 €/kg$H_2$ lower than the common production cost of hydrogen ranging at 1 €/kg$H_2$ to 3 €/kg$H_2$ (Kopp et al., 2017).

Hou et al. (2017) examined the investment potential of coupling offshore wind power with hydrogen systems, including electrolysers and PEM FC in Denmark. The paper also investigated the trade-offs between selling the produced hydrogen to end consumers or using it for re-electrification. The optimisation of the first investigated case, where the hydrogen is produced during the lower electricity market prices and used for re-electrification when electricity market prices were high, showed that it was not economically viable due to limited number of hours with sufficient high price differentials in the market. For the second P2G case study, the optimal power capacity of the electrolyser for the scenario of a hydrogen fuel cost of 2 €/kg$H_2$ (or 36.4 €/MWh) has been calculated to 5.5 MW based on the electricity market price during the examined time period and the payback period of the investment to 24.4 years. Similarly, for the scenarios of a hydrogen fuel cost of 5 €/kg$H_2$ and 9 €/kg$H_2$, the electrolyser capacity has been calculated to 13.5 MW and 23.4 MW, while the payback period to 5.5 and 2.6 years, respectively. Concerning the latter scenario, the quantity of $H_2$ produced by the electrolyser reaches 5,000 kg/day, which can be either used in the petroleum processing and/or the transportation sectors (Hou et al., 2017).

The integration of a WH system with a demand-response scheme has been investigated by Mirzaei et al. (2019) focussing on a stochastic security-constrained unit commitment based on different scenarios. The hydrogen storage capacity was set to 180 MWh, while the minimum reserve capacity was assumed to be 40 MWh. The four investigated cases were: stochastic operation of the wind farm, integration of price-based demand-response, integration of the hydrogen system in the stochastic operation and integration of the hydrogen system and the demand-response scheme in the stochastic operation. The results indicated that the lowest operating cost and lower wind power curtailment were observed in the fourth case followed by the second and the third. However, the introduction of the hydrogen storage topology alone (i.e. case 3) showed the second lower wind power curtailment after case four (Mirzaei et al., 2019).WH systems are subjected to the intermittent production of wind energy, and often large wind power fluctuations may limit the ideal operation of the water electrolysis systems. Fang and Liang (2019), simulated the operation of a WH grid-connected system in China coupled to a supercapacitor in order to smooth large variations of wind-produced electricity powering an alkaline electrolysis system consisting of five 3 MW modules. The system's operation is optimised through a modular adaptive control strategy that regulated the start-stop operation of the hydrogen production units. The simulation results were compared to simple start-stop strategies and showed an increase of hydrogen production by 44.18%, while at the same time the switching times were reduced by 93.5% (Fang and Liang, 2019).

Fang (2019), has also studied the LC cost of a hypothetical hydrogen production system coupled to an existing 49.5 MW wind farm in South China within a life cycle of 20 years. The hydrogen system would produce $H_2$ from otherwise wasted wind energy and then would fuel a FC which in turn would support the electrical grid by improving the power quality of wind power. The results of the study showed that the payback period of the WH-FC system would be less than the wind farm alone at 8.13 years from 11 years (wind farm alone), whereas the payback period in the case of no FC in the system would reduce to 7.78 years (Fang, 2019).

**4.1.3.1.1. Analysis of the results for the grid-connected WH systems**

Many of the above-mentioned studies focused on case studies regarding WH systems installed in specific regions. Fig. 4.1.3 shows the regions that some of the above studies focused on.

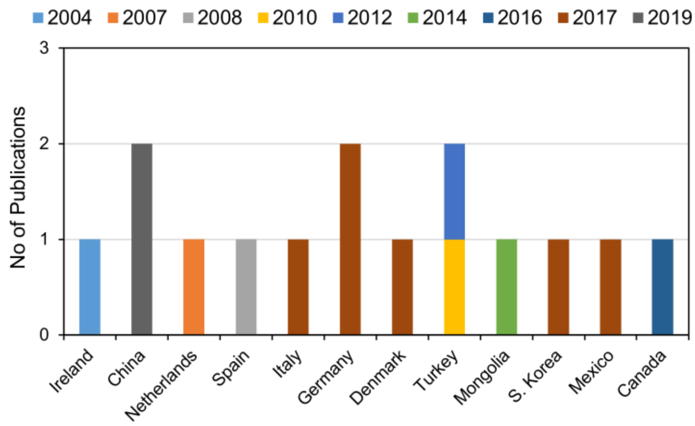



Fig. 4.1.3. Grid-connected WH system analysis by country.

According to Fig. 4.1.3, one may extract two conclusions. Firstly, most of the studies focused on European countries, followed by Asia and America, and secondly, the majority of the studies were published over the past three years.

Through the comparison of the data presented in the previous sub-section of this study, it is apparent that the existing literature focussed on either technical or financial or both techno-economic and environmental aspects of the subject. In relation to financial evaluation, Schenk et al. (2007) although suggested that the production of hydrogen would occur at low cost of electricity, they did not provide data regarding the cost viability of such a project. At the same pattern, García Clúa et al. (2011), Alvarez-Mendoza et al. (2017) and Guandalini et al. (2016) analysed the operation of a WH system but no financial evaluation was provided. The majority of the presented articles examined the levelised cost of hydrogen fuel providing values depending on the characteristics of each system, the application and the different case studies.

It is worthy to mention that in some cases the values given for the levelised hydrogen cost, indicate large deviations between each other. The cost range given by Gökçek (2010) seems rather low regarding the minimum value, and it suggests an extremely low or even negative grid electricity price, which might be too optimistic for the majority of countries. By comparing also the studies of Gökçek (2010) and Genç et al. (2012) held in different regions of Turkey, it can be seen that the levelised cost of hydrogen presents a large interval, which suggests the high dependency of the available wind resource in each area on hydrogen production. Most of the studies however, demonstrate a mean cost of $H_2$ of approximately 6 €/kg$H_2$, which is supported from a report by NREL showing a hydrogen cost range between 2.6 and 8.8 €/kg$H_2$ for grid connected systems (Eichman et al., 2016).

#### 4.1.3.2 Experimental and simulated operation of stand-alone WH systems for covering the electricity demand at autonomous grids

During the last 20 years, data from autonomous WH system simulations and experimental results based on real operation of pilot projects have revealed the prospects of hydrogen technologies coupled with wind energy converters for covering the electricity demand in remote and/or autonomous electrical networks. Dutton et al. (2000) assessed the technical and economic aspects of the operation of electrolysers under fluctuating power output of wind turbines, which resulted in a demonstration plant being built at ENEA's Casaccia Research Centre in Italy. The operation of the electrolyser under intermittent supply presented no stability problems; however, at low capacity factors, the operation led to reduced performance and $H_2$ gas quality. The research revealed that in the case of a WH system located in an area with good wind resource, hydrogen price may reach 0.2 DM/kWh$_{H2}$, which corresponds to approximately 3.9 €/kg$H_2$ based on hydrogen's HHV (Dutton et al., 2000).

Varkaraki et al. (2006) have presented the results obtained during the operation of the RES2$H_2$ project in Greece. The pilot system comprised a wind (500 kW) electrolysis system (25 kW) for producing and storing hydrogen gas in high-pressure tanks or metal hydrides. The efficiency of the system included all the main and auxiliary components for the production, compression and storage of hydrogen, and ranged between 50% and 60%. The electrolysis efficiency decreased at higher current densities and lower operational temperatures, and ranged between 70% and 85%. To retrieve the $H_2$ stored in the metal hydride tanks and sustain the desorption process, a boiler was used with its energy demand representing the 30% of the $H_2$ energy content due to bad insulation of the system (Varkaraki et al., 2006). Likewise, Ulleberg et al. (2010) published a comparative analysis of the pilot WH system, including a WT, an electrolyser, an FC and an $H_2$ generator in the island of Utsira in Norway during four years of operation and simulation data. The operation of the system demonstrated an efficiency of the system of 53% and the main outcome suggested that this kind of topologies could supply a remote community. However, technical improvements and cost reduction are of major importance. For utilisation of more than the 20% of the available wind-produced energy, it is required to install more suitable and efficient electrolysers capable of operating dynamically (Ulleberg et al., 2010).

In the context of real experimental data, Valverde-Isorna et al. (2016) developed a model of the wind water electrolysis PEM FC system installed at the 'Hydrogen office building' in Scotland. The experimental validation of the model was based on real data taken during the operation of the system. The authors initially described the model, and based on the experimental data, they calculated the empirical factors introduced in the model. Moreover, this paper examined four scenarios of different average wind speeds, showing 100% energy autonomy with an efficiency above 60% for high wind speeds. In contrast, for medium and low wind speeds, energy autonomy and efficiency decreased to 11% and 52%, respectively (Valverde-Isorna et al., 2016). A more recent experimental study compiled by Bhogilla et al. (2017) comprised an analysis of a lab-scale WH system, including a unitised reversible FC, hydrogen storage tank and auxiliary components. The authors evaluated the electrolyser and FC operating modes under dynamic operation based on intermittent wind power. The experiments demonstrated that the system was able to respond to a dynamic wind power input. In electrolyser mode, efficiency reached 81% while in FC mode at maximum output power, the stack efficiency reached 44% and the FC system efficiency 24% due to increased heat generation at high current densities. The maximum total efficiency of the unitised reversible FC was 53%, and the maximum total efficiency of the hydrogen system was 66%, including the heat output of the unitised reversible FC (Bhogilla et al., 2017). In this regard, Gandía et al. (2007) published the results of the operation of an electrolysis system powered by emulated wind conditions. The outcome showed that the efficiency of the electrolyser was between 74% and 83%, and its response to the dynamic conditions of wind power input was fast (Gandía et al., 2007).

Besides the presentation of experimental data, many studies examined the operation of WH systems via simulations for either supplying electricity to remote communities or covering the energy demand of specific applications. Iqbal (2003) modelled a small hybrid energy system consisting of a wind turbine, a PEM FC and an electrolyser. The simulation results indicated that the fluctuating wind power caused voltage variations of the 48 V system ranging between 43 V and 65 V. The simulation determined the controllability and expected transients of the hybrid system (Iqbal, 2003).

Bechrakis et al. (2006) demonstrated a simulation and assessment of an autonomous WH system, including an FC installed at remote hotel premises. The best scenario in terms of covering the hotel's summer electricity demand under the lower produced electricity costs (1.31 €/kWh) included a 20 kW WT, a 6 kW electrolyser, 900 $Nm^3$ of $H_2$ storage and a 10 kW FC. The annual simulated operation of the system revealed that the FC could generate 3,320 kWh resulting to significant GHG avoided emissions in the case where the electricity supply of the hotel would be covered by diesel generators (Bechrakis et al., 2006).

Sovacool and Hirsh (2008) investigated different small island regions located in the UK, Norway and Denmark in terms of WH FC systems for applications, including grid support/security and transportation. The deployment of WH FC schemes in islands with harsh wind conditions indicated that these could provide great value when it comes to reducing high energy costs and the concern for economic development. However, challenges include, among others, the development of WTs able to exploit extreme winds as well as the need for more economic and political analyses on these systems (Sovacool and Hirsh, 2008).

Khan and Iqbal (2009) presented a modelling and simulation study of a small WH system, including an FC, where a detailed simulation of all components indicated successful operation. However, model validation is suggested by the authors to be a very important next step (Khan and Iqbal, 2009).

Storage of the produced hydrogen gas is also of great importance to an autonomous WH system. Zini and Tartarini (2010) presented a modelling and simulation of a wind electrolysis FC with carbon physisorption $H_2$ storage. The simulations showed that such a system could operate without grid support but with an overall efficiency (including wind) of approximately 10%. For $H_2$ storage, a carbon tank volume has been calculated to 0.38 $m^3$ for storing 12.4 $kgH_2$ at 6 MPa. The same $H_2$ amount as gas storage at the same water volume would require a pressure of 40 MPa (Zini and Tartarini, 2010). Other simulating studies also analysed different operational parameters of the water electrolysis process. During their model development, Pino et al. (2011) took into account the thermal inertia and operating temperature of the water electrolysis process. The simulations indicated that the power curve of the WT does not fit well with real data providing overestimated results (25-33.6%). Operating temperature of the electrolyser presents a difference of 3% of higher hydrogen production for the static compared to the dynamic simulations (Pino et al., 2011).

Island regions are usually autonomous systems, and, therefore, a WH stand-alone arrangement may present a viable solution for covering their energy requirements. Apostolou (2015) developed an analytical modelling and simulation of a hydrogen production-storage system for storing energy from wind curtailments in an autonomous system. The system comprised an alkaline electrolyser $H_2$ gas storage and metal hydride storage. The results showed that an electrolysis system of an 8 MW rated power is able to store the highest amount (≈71%) of rejected energy from a 10 MW wind farm located in a Greek island. The overall average efficiency of the hydrogen production unit has been found to be approximately 73% (HHV-based) (Apostolou, 2015).

Kaldellis et al. (2015) also investigated a wind electrolysis FC system to support high wind power penetration and provide energy autonomy in Greek non-interconnected islands. The under investigation case study revealed that the round trip efficiency of such a system is low, reaching a maximum of 50%, while a WH system comprising a 10 MW wind capacity along with a hydrogen-based storage in the order of 350-400 MWh is required for an autonomous one week operation with a mean hourly energy demand of approximately 550 MWh (Kaldellis et al., 2015). Similarly, Chade et al. (2015) presented a feasibility study of WH systems to support diesel generators in remote Arctic locations such as Grimsey island in Iceland. Three scenarios have been analysed: wind/diesel, wind/diesel/hydrogen and wind/hydrogen. The first scenario showed a decrease in the demand for diesel by 50% and an increase of excess wind energy by 70%. In the second scenario, the introduction of a hydrogen system decreased the demand for diesel by 80% and reduced excess wind by approximately 25% compared to the first scenario. Although in the third scenario the demand for diesel was equal to zero for having 100% energy independency, the system's capital and operational costs together with the cost of electricity proved to be significantly higher in the long term than a diesel-based system (Chade et al., 2015).

Kavadias et al. (2018) published an optimisation and modelling method of a RES-hydrogen system located in a Greek island autonomous network, utilising wind curtailment to support the grid-connected FC when needed or for transportation purposes in relation to FCES. The algorithm presented in this research calculated that an electrolyser of 1.26 MW would absorb the highest amount of rejected power coming almost entirely from wind farm installations. The total average efficiency of the hydrogen production-storage reached 57%, while the annual production of hydrogen was calculated to 7,272 kg. For supporting the electrical network, two scenarios were analysed comprising 1) grid support only during high electricity demand in order to minimise the fossil fuel-based generation by injecting 155 MWh of FC produced electricity, and 2) direct $H_2$ supply of the FC based on the electrolyser's production. In the case of using the produced hydrogen to refuel FC ES, it was calculated that approximately 263 vehicles can be operated on a daily basis (Kavadias et al., 2018).

Similarly, Enevoldsen and Sovacool (2016), studied the potential of replacing a diesel-based electricity production system located at the small island of Mykines in the Faroe Islands with a WH system comprising four 22 kW WTs, an electrolyser of maximum $H_2$ production of 8 $Nm^3/h$, and a FC system of five 10 kW stacks. The results of the research showed a LCOE for the WH system of 0.47 €/kWh, while for the diesel generators the maximum levelised cost has been calculated to 0.34 €/kWh.

Regarding the avoided GHG emissions achieved by the substitution of the diesel generator, the authors demonstrated that the annual $CO_2$ abatement might reach 171.7 t (Enevoldsen and Sovacool, 2016).

Assessment of WH systems to cover residential energy demand is also of great interest. Hacatoglu et al. (2016) studied a wind electrolysis FC system to cover the heating, cooling and electricity demand of a small community in Canada by using the ISI. In addition, they compared the under investigation system with a conventional gas-fired one. For this configuration, ISI ranged between 0.56 and 0.84, whereas the ISI for the gas-fired plant ranged between 0.52 and 0.86. Through comparison of the ISI for both technologies under different perspectives, the authors concluded that gas-fired systems present a slightly higher individualist ISI due to more affordable energy for the community, while the WH system presents a higher egalitarian ISI because of better environmental performance (Hacatoglu et al., 2016). Ishaq et al. (2018) examined a WH system, including an FC for providing heat and electricity to a household community of 25 houses. Hydrogen is primarily produced from excess wind power and used through the FC to overcome the electricity shortages at low wind speeds. The efficiency of the system at higher wind speeds (9 m/s) reached 39.5%. At low wind speeds, the system provided heat and electricity through the FC with an increasing system efficiency as wind speed decreases (30% at 1 m/s) (Ishaq et al., 2018).

Babarit et al. (2018) presented a rather innovative research. The authors examined the potential of autonomous fleets of sailing wind energy converters with hydrogen storage to exploit open sea high wind resource. An economic evaluation of the transportation and distribution of the produced hydrogen fuel was also conducted. The results of the study demonstrated that with an on-board electricity cost at 0.08 €/kWh, the delivered $H_2$ costs would range between 7.1 €/kg$H_2$ and 9.4 €/kg$H_2$ depending on scenarios of $H_2$ compressed gas or $H_2$ liquid storage, transportation type (i.e. trucks or pipelines) and the delivery distance (Babarit et al., 2018).

An investigation of the operation of a stand-alone WH system in the Kanin Nos Cape in the Arctic as an uninterrupted power supply was published by Solomin et al. (2019). The system's main components comprised a small vertical-axis 3 kW wind turbine, an alkaline electrolyser with rated $H_2$ output of 0.44 $Nm^3/h$, and a FC of 1 kW. The outcome of the operation of the pilot configuration showed that such topologies can be scaled accordingly in order to cover a power demand of up to 50 kW in similar severe climatic conditions. In terms of financial evaluation, the authors calculated that based on the capital cost of the system and the operating costs of an alternative solution based on diesel generators, the payback period would be 7 to 10 years (Solomin et al., 2019).

Ayodele and Munda (2019) presented a research on the potential of hydrogen storage systems for different wind resource sites in South Africa investigating different wind turbine scenarios. The authors calculated that the best hydrogen production potential and the lower cost per produced $kgH_2$ was found for the site near the town of Napier and depending on the wind turbine type these values ranged between 6.51 and 226.82 metric tons of $H_2$ per year, and 1.24 and 35.04 €/$kgH_2$ respectively. However, for small wind turbine schemes in some regions the cost of hydrogen was demonstrated to reach even 139.27 €/$kgH_2$, which dictates that WH systems coupled to higher wind power capacities seem to be more cost efficient in regards to the $H_2$ fuel cost (Ayodele and Munda, 2019).

#### 4.1.3.2.1. Analysis of the results for the stand-alone WH systems

The presented studies regarding stand-alone WH systems indicate the significance of energy storage topologies such as a hydrogen production system used to support weak autonomous electrical networks and allow higher integration of RES power in remote non-interconnected areas. Fig. 4.1.4 below summarises the literature review results concerning the pilot and simulated autonomous systems by country and year.

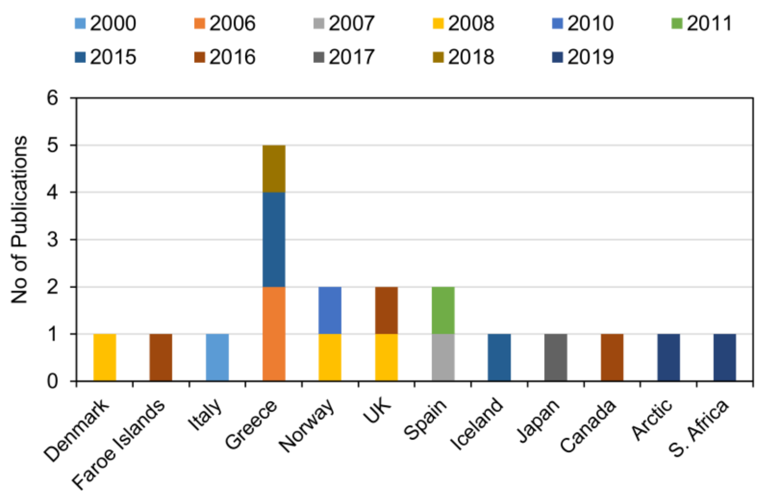



Fig. 4.1.4. Studies on both experimental and simulated WH autonomous systems by country.

Based on Fig. 4.1.4, it is apparent that similar to the previous research on WH systems, most studies either examine pilot projects or simulated case studies located in Europe. The literature review revealed a particularly high number of publications in Greece. This happens because, compared to other European countries, Greece's electrical grid is divided in two sectors, one of the interconnected mainland, and another of the non-interconnected islands comprising 32 autonomous grids (HEDNO, 2018). To this end, there is a huge interest in Greece for RES energy storage technologies, including WH configurations.

From the efficiency and the overall operating behaviour perspective of the WH systems in autonomous electrical grids, the above-mentioned studies showed similar efficiencies for the $H_2$ production-storage process ranging between 50% and 60%. Additionally, in all cases the technical evaluation of the projects demonstrated positive results in relation to the integration of the WH system in the local grid. However, it should be noted that hydrogen technologies coupled with RES topologies are still at an infant stage, suggesting the existence of drawbacks involving both technical and financial parameters.

Two of the main issues the local communities face in autonomous electrical networks is the high electricity price and the environmental impacts caused by the oil-based electricity generation technology that dominates in such regions. The effect of a WH system in the electricity prices has been demonstrated by Sovacool and Hirsh (2008) and Enevoldsen and Sovacool (2016) showing almost the same levelised cost between the WH and the diesel system configurations. On the other hand, the implementation of a WH system in autonomous networks is argued to decrease significantly the GHG emissions by either reducing the fuel demand of diesel generators or by replacing entirely the fossil fuel generation (Bechrakis et al., 2006; Chade et al., 2015; Kaldellis et al., 2015; Kavadias et al., 2018).

#### 4.1.3.3 WH systems for covering the demand of H2 for transport applications

The concept of using hydrogen as a fuel for transportation is not new; following the 1973 oil crisis, many automobile industries presented prototype hydrogen-powered vehicles. However, it was not until the mid-1990s that the first experimental passenger FC car was developed by Daimler-Benz [70]. Other car industries followed the example of Daimler-Benz, but none of these prototype models entered the market. After the introduction of the first commercialised FCEV in the market since 2015, aiming to support the transition to more environmentally sustainable means of transportation, many scientific studies investigated the potential of producing hydrogen for transportation by using RES instead of NG reforming processes (Nikolaidis and Poullikkas, 2017). In this context, Shafiei et al. (2017) studied the potential of hydrogen-propelled vehicles in future scenarios for the mitigation of the GHG emissions from the transportation in Iceland. The authors pointed out the environmental benefits of implementing hydrogen technologies in transportation instead of solely battery electric vehicles (Shafiei et al., 2017).

Greiner et al. (2007) presented a sizing and optimisation algorithm of a WH energy system located in a Norwegian island based on the demand of a $H_2$ propelled ferry. The study also included a comparison of a grid-connected and an isolated system. To cover the daily $H_2$ demand, a 2.3 MW WT, a 1 MW electrolyser and $H_2$ storage of 680 kg are required for a grid-connected system giving an $H_2$ cost of 2.8 €/kg$H_2$. For the stand-alone system, a 3 MW WT, a 2 MW electrolyser and $H_2$ storage of 3,400 kg are required, increasing the $H_2$ cost to 6.2 €/kg$H_2$. By using the produced hydrogen as fuel for the $H_2$

propelled ferry, the avoidance of emissions might reach 1940 t/yr and 14.6 t/yr for $CO_2$ and $NO_x$ respectively based on the case of the grid connected WH system (Greiner et al., 2007).

Mathur et al. (2008) have assessed the economic potential for producing hydrogen from onshore and offshore wind and use it as transportation fuel in India. For cluster capacities below 100 MW, the hydrogen cost per MJ was found to be very high (17.7 €/MJ). At higher capacity values, the contribution of the transmission system decreased, and therefore, $H_2$ cost lowered. Similarly, moving to offshore, the energy yield increased, resulting in a cost reduction of 20.2% for a 100 MW cluster capacity (Mathur et al., 2008).

Grüger et al. (2018) argued that in order to achieve low $H_2$ fuel costs for transportation, it is required to optimise the water electrolysis process while operating at low electricity costs and combined with wind energy. The results obtained from the application of a model taking into account forecasts of wind availability or energy prices showed a reduction of hydrogen production costs by 9.2%. Furthermore, the wind energy utilisation presented increased by up to 19%. Two scenarios were investigated, including one with on-site $H_2$ production during low energy prices, and one with an identical station but with an additional WT of 1.6 MW, which supplied a higher rated power electrolyser compared to the first scenario (Grüger et al., 2018).

Regarding hydrogen refuelling stations for light-duty vehicles, Apostolou et al. (2019) analysed the potential of a small-scale $H_2$ refuelling station powered from a WT to support urban FC bicycle fleets in Denmark. The study provided a methodology for the sizing and optimisation of the components of a small-scale $H_2$ refuelling station based on the wind resource of a region. The outcomes showed that to cover the daily $H_2$ demand of a fleet of 1,149 FC electric bicycles in an small city in Denmark, the on-site hydrogen production would require energy from a 50 kW WT, an electrolyser of a 70 kW rated power and an $H_2$ storage tank of 7.3 $m^3$ (Apostolou et al., 2019).

In the context of autonomous hydrogen refuelling stations, Messaoudi et al. (2019) developed a methodology for site selection of hydrogen refuelling stations with on-site hydrogen production powered from wind energy. The authors examined a case study for the region of Adrar in Algeria and they followed an analytical hierarchy process belonging to the multi-criteria decision-making tools in order to identify which of the available petrol stations can be reverted to $H_2$ refuelling stations. Out of 24 conventional petrol stations in total, 15 were investigated and only 4 sites were found suitable for wind powered on-site $H_2$ stations. The rest 11 however, could be modified as off-site hydrogen stations in the retail refuelling market (Messaoudi et al., 2019).

Based on the presented data from the above-mentioned studies, it is apparent that the introduction of WH systems for supporting hydrogen mobility is a positive contribution towards 'greener' transportation in terms of sustainability and GHG emissions reduction. Nevertheless, the $H_2$ fuel price is highly dependent on the application and the size of the system. For instance, in the case of hydrogen-propelled sea vessels and hydrogen production through electrolysis powered by existing wind farms, the levelised hydrogen fuel cost may be relatively low and comparable to oil fuel price due to the size of the hydrogen system in conjunction to the respective fuel demand. In contrast, in the case of small scale applications (e.g. light and medium-duty road vehicles), although the capital investment seems rather lower than large applications, the levelised cost of the $H_2$ fuel highly depends on the type of refuelling stations (i.e. on-site vs offsite $H_2$ production and daily $H_2$ storage capacity), the fuel demand (i.e. number of vehicles), and the electricity prices.

#### 4.1.3.4 LC assessment of WH systems

One of the most significant methods for the evaluation of the environmental performance of products and technologies comprises the LC assessment, which investigates different stages found in the development of a project from design to trade. This includes resource extraction, manufacturing, transport, operation, and end-of-life disposal, focussing on the environmental aspects of those different processes (Yang, 2017).

Both grid-connected and autonomous WH systems are based on the logic of using wind energy to power an electrolysis unit and then either use the produced hydrogen in re-electrification through a FC or as a gas fuel in several processes (see Fig. 4.1.2). This energy flow of the system produces in general no to low GHG emissions in the case where operation of the auxiliary components such as pumps or compressors are supplied from the main electrical grid (in grid-connected systems). However, in a LC assessment analysis it is necessary to include also the processes of manufacturing and decommissioning, which consist a major contribution to environmental impacts of wind power and other RES based projects (Mendecka and Lombardi, 2019; Zhao and Pedersen, 2018).

In this regard, Koroneos et al. (2004) presented a LC assessment for $H_2$ production systems powered from various RES. The authors' results showed that the total impact score of hydrogen production from wind power comprising GHG emissions, acidification, eutrophication and winter-smog was significantly lower than other RES-hydrogen systems. Regarding GHG, the $CO_2$ equivalent emissions from a WH system were found to be less than 0.3 $kgCO_2$-eq/kWh, while for a similar system but with a photovoltaic power source, the $CO_2$ equivalent emissions found to be more than 0.4 $kgCO_2$/kWh (Koroneos et al., 2004).

Spath and Mann (2004), published a report presenting the results of a LC assessment concerning a WH system comprising three 50 kW wind turbines and an electrolyser of 30 $Nm^3/h$ nominal hydrogen outlet flow rate. Based on the resource requirements, the transportation of the different components to the specific installation site and the operation of the system, it has been demonstrated that the majority of the global warming potential arises firstly from the construction and operation of the wind turbine and secondly from the compression and storage of hydrogen. Specifically, out of the total 0.98 $kgCO_2$-eq/$kgH_2$, 78% comes from wind turbine construction and operation, 4.4% are emitted from the electrolysis production and operation, and the rest 17.6% comes from the $H_2$ compression and storage process (Spath and Mann, 2004). However, this report did not included the final disposal environmental impacts in the final calculations.

The investigation of an autonomous WH system from a LC assessment perspective was disseminated by Zhao and Pedersen (2018). The examined configuration included apart from the wind turbine, the electrolysis and the $H_2$ storage, the transportation of the hydrogen to a FC site for supplying power to a building and to a refuelling station for FCEVs as the end-user. The results of the study showed a global warming impact of 1.78 $kgCO_2$-eq/$kgH_2$, which accounts to a reduction, if compared to NG-based electricity production, by 7.81 $kgCO_2$-eq/$kgH_2$. Concerning the scenario of using the produced hydrogen for transportation purposes, the LC assessment showed a decrease of the carbon footprint by 13.40 $kgCO_2$-eq/$kgH_2$ if the substituted vehicles were electric. However, in both cases the study demonstrated that hydrogen implementation in the energy system may introduce impacts like ozone depletion, human toxicity and non-renewable resource depletion (Zhao and Pedersen, 2018).

In the context of hydrogen utilisation in the transportation sector, Wulf and Kaltschmitt (2018) assessed the environmental performance of different hydrogen supply chains in order to support a growing fleet of FCEVs in 2032. Among all the investigated technologies, the LC assessment of WH systems showed the lowest climate change impact with 0.95 $kgCO_2$-eq/$kgH_2$ for alkaline electrolysis and 1.06 $kgCO_2$-eq/$kgH_2$ for PEM electrolysis. In contrast, the LC assessment concerning production of $H_2$ by steam methane reforming process showed a climate change impact of 11.98 $kgCO_2$-eq/$kgH_2$. Significantly lower values for the WH systems are also observed for acidification, eutrophication, ozone creation, particulate matter, and human toxicity, when compared to other production methods (Wulf and Kaltschmitt, 2018).

Mehmeti et al. (2018) on the other hand, included in the LC assessment of various hydrogen production methods the water footprint of all the under investigation technologies. According to their results the water electrolysis-based WH production scheme compared to conventional steam methane reforming presents lower indicators in some of the LC assessment categories including global warming potential, stratospheric ozone depletion and fossil resource scarcity, while for others such as water consumption potential, land use and non-cancer human toxicity, the indicators for steam methane reforming technology seemed to be more advantageous (Mehmeti et al., 2018).

In terms of environmental impact assessment of WH systems, Ghandehariun and Kumar (2016) performed a LC assessment of such topologies installed in Canada. The outcome of their research showed that the overall GHG emissions of the proposed system presented 94% lower emissions than conventional fossil fuel systems. The LC emissions of the proposed system ranged between 0.63 and 0.73 kg $CO_2$ eq. per kg of $H_2$ (Ghandehariun and Kumar, 2016).

### 4.1.4 Discussion

As it is apparent from the results obtained through the review process of previous studies on WH systems, there are some advantages, yet also drawbacks in the use of this technology combined with wind power schemes.

In almost all the presented studies, the authors concluded that with the implementation of hydrogen-based technologies in conjunction with wind energy systems, wind penetration to the grid increased and power curtailments were lowered significantly. Additionally, many studies indicated high hydrogen production efficiencies ranging between 70% and 87%, while with the introduction of $H_2$ storage, efficiency decreased to 50-65% (see Fig. 4.1.5). The higher efficiency interval observed at the electrolysis process (i.e. left section of Fig. 4.1.5), corresponds to the electrochemical efficiency of the water electrolysis and it is supported through the theory of thermodynamics, which suggests a thermodynamic efficiency greater than 100%. However, in reality electrolysers operate at cell voltages higher than the thermoneutral voltage (i.e. 1.48 V) and thus their efficiency drops below 100% due to heat losses (O'Hayre et al., 2016). On the other hand, in addition to possible hydrogen leaks through the piping system, the introduction of other components in an electrolysis storage system such as $H_2$ compressors lowers the efficiency of the plant to values below the electrochemical efficiency (i.e. see mid-section of Fig. 4.1.5). A WH system can be used for re-electrification by including a FC in the configuration. The introduction of a FC reduces further the round-trip efficiency of the system (i.e. see right section of Fig. 4.1.5) by at least 83%, which corresponds to the maximum theoretical efficiency of the FCs (O'Hayre et al., 2016).

Based on the simulations and the pilot project experimental data, a hydrogen system, including the production, storage and utilisation stage, is able to provide ancillary services by following the load continuously and supporting the grid when this is required. Another technical benefit of a WH system is that in autonomous islands or small remote communities, where diesel generators dominate, WH systems reduce the demand for diesel and consequently benefit the environmental factors of the specific regions. From a business perspective, hydrogen systems coupled with wind energy may be economically appealing, but the fuel costs of $H_2$ should not be less than 9 €/kg$H_2$ in order to have substantial revenues and shorten the payback period to a few years.

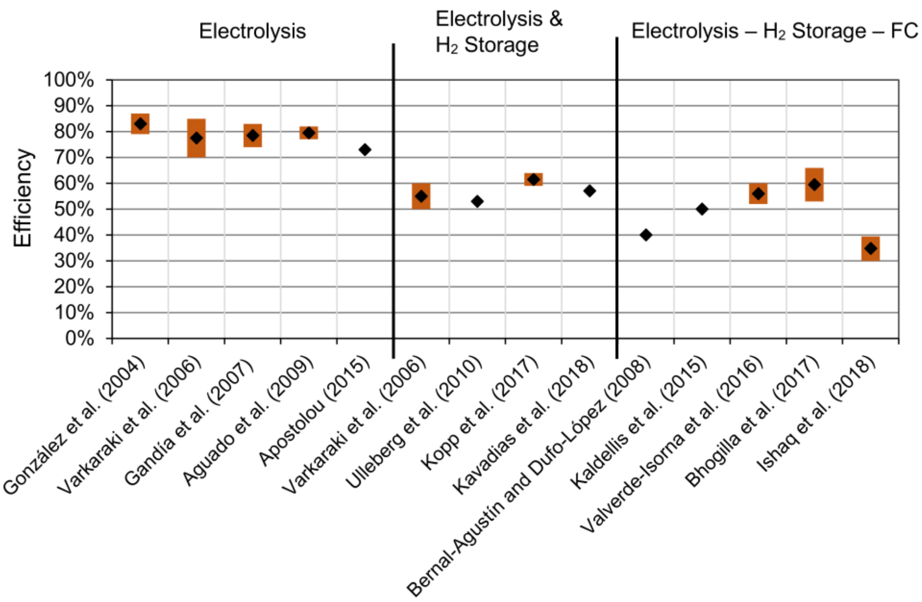



Fig. 4.1.5. Energy efficiency of different hydrogen configurations.

However, the operation of a WH system for increasing wind penetration as well as supporting the grid or for producing hydrogen fuel presents several disadvantages, which hinder its further exploitation as a main RES energy storage method. Many research studies have focused on the effectiveness of a hydrogen system coupled with wind energy. Based on their results, it seems that although the technologies used in such systems can be considered mature, they present complexity when combined together, and the frequency of operating faults increases.

Additionally, as seen from Fig. 4.1.5, the round-trip efficiency of a hydrogen system, including the production, storage and utilisation of hydrogen processes, is low compared to other energy storage technologies. In addition, it ranges between 30% for residential applications up to 66% with the majority of the studies indicating values of 50% to 60%. A significant drawback of these energy storage arrangements also comprises their capital and operational costs based on the cost of electricity for the production of hydrogen. Moreover, the uncertainty span of the efficiency presented in Fig. 4.1.5 has to be noticed as e.g. Varkaraki et al. (2006) presented a difference of 15% between minimum – and maximum efficiency for the stand-alone electrolysis, and Bhogilla et al. (2017) presented a difference of 13% when including storage and FC. Furthermore, the differences between max and minimum mean values ranges from 73%-83% for the electrolysis process, 40% to 62% for the electrolysis and storage, and finally from 35% to 60% for the electrolysis, storage, and FC. These uncertainties have to be taken into consideration when reviewing and planning for viable WH systems.

High investment and operational cost of a hydrogen system coupled with RES result in an increased cost per kilogram of $H_2$ fuel in order to have an economical viable business scenario. According to Fig. 4.1.6, hydrogen costs have been found to reach even 26 €/kg$H_2$, but most studies indicate numbers up to 10 €/kg$H_2$ to balance the high investment costs. In the case of autonomous systems that operate under thermal-based electricity generation, a total replacement of the existing conventional technologies with a WH system would require a high capital and operating cost, which would increase the cost of electricity for the remote community significantly.

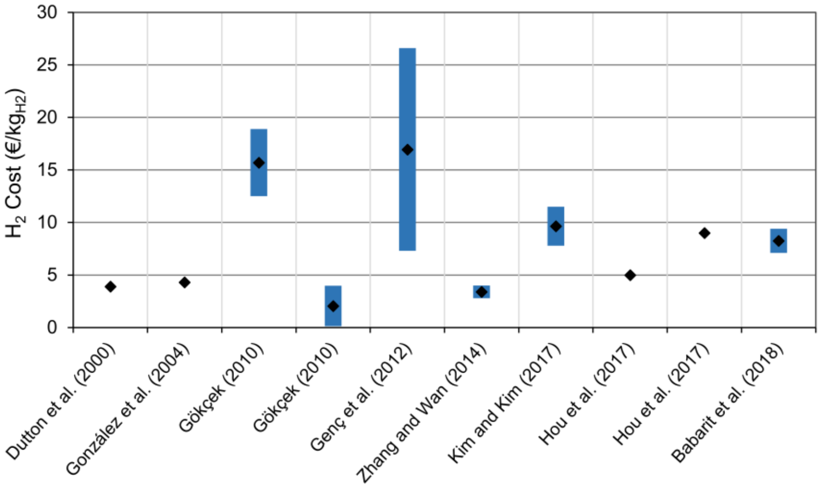



Fig. 4.1.6. Hydrogen costs for having an economically viable WH system.

An increasing hydrogen demand beyond storage is expected in the coming decades (Brown, 2016b), which was further supported by this literature review, indicating an increasing interest in transportation in recent years (see Fig. 4.1.1). This naturally raises a question on electricity supply for electrolysers, while future research may debate if wind turbines are to be considered a service technology for electrolysers, and not vice versa. However, this study emphasises that for now, risks such as the uncertainty of the performance of the hydrogen system, just as the fluctuant behaviour of the wind, has to be taken into account when assessing the cost of hydrogen. The literature review revealed that the forecasted hydrogen demand mainly can be divided into groups of energy storage, ancillary services and transportation ranging from hydrogen bikes to ferries.

Concerning the environmental benefits arising from the implementation of WH topologies, it is apparent based on the reviewed studies that avoidance of GHG emissions in the electricity production and the transportation sector are significantly lower depending on the scale of the WH system. The LC assessment of WH topologies presented in the previous section of this paper, showed lower indicators in the LC categories compared to other hydrogen production methods. The most important advantage in all assessments was argued to be the low climate change impact, which ranged in all studies between 0.95 and 1.78 kg$CO_2$-eq/kg$H_2$. Table 4.1.1 synopsises the results presented at the previous sections, and by taking into account a range of $CO_2$ emissions per $kWh_e$ produced by conventional power plants (450 – 1050 g$CO_2$/$kWh_e$) (Kaldellis and Apostolou, 2017), the authors calculated the avoidance of $CO_2$ from the use of WH systems wherever this was not demonstrated in the reviewed studies. Moreover, in the case of hydrogen-based transportation the authors estimated the $CO_2$ avoided by replacing conventional vehicles with FC vehicles considering that the range of FC vehicles is approximately 100 km/kg$H_2$ (Adolf et al., 2017) and that on average $CO_2$ emissions of contemporary vehicles equal to 112.2 g$CO_2$/km (Magueta et al., 2018).

Table 4.1.1. Annual $CO_2$ emissions avoided from the electricity generation and transportation sectors by the implementation of WH systems.

| **Source** | **WH system (Wind Power; Electrolysis; FC)** | **Annual $CO_2$ Emissions Avoided (t)** | |
|---|---|---|---|
| | | **Electricity Production** | **Transportation (vehicles)** |
| (González et al., 2004) | 5 GW; 30 MW | $8.4 \cdot 10^6$ | $1.6 \cdot 10^6$ |
| (Gökçek, 2010) | 6 kW; 2 kW | 6.8 – 15.9 | 1.1 (road) |
| (Zhang and Wan, 2014) | 99 MW; 1 MW | $43.5 \cdot 10^3$ | - |
| (Guandalini et al., 2015) | 16 GW; 620 MW | $147 \cdot 10^3$ | - |
| (Hou et al., 2017) | 72 MW; 23.4 MW | - | $20.5 \cdot 10^3$ (road) |
| (Bechrakis et al., 2006) | 20 kW; 6 kW; 10 kW | 1.5 – 3.5 | - |
| (Kavadias et al., 2018) | 15.2 MW; 1.26 MW | 67.5 – 157.5 | or 81.6 (road) |
| (Enevoldsen and Sovacool, 2016) | 22 kW; 45 kW; 50 kW | 171.7 | - |
| (Greiner et al., 2007) | 3 MW; 1 MW | - | 1,940 (ferry) |

According to the data presented in Table 4.1.1, the environmental benefits of the deployment of WH systems either in grid connected or autonomous configurations are significantly favourable in terms of lower GHG emissions. The annual $CO_2$ avoidance is in the order of tonnes and depending on the size of the system, it can contribute positively towards a cleaner energy production and utilisation in the mobility and electricity sector.

### 4.1.5 Conclusions and future prospects

This study has introduced the current state of hydrogen by investigating 40 papers, which have either simulated or described WH systems installed in different configurations and for different purposes. WH systems have been analysed in various countries, indicating the distributed potential of hydrogen as a storage application as well as an important global energy source.

The literature study revealed that academia has divided WH systems into three main categories. First, grid-connected WH systems where hydrogen acts an ancillary service, which is very a profitable solution for countries and/or market with high penetrations of wind power. Second, stand-alone WH systems with the main purpose of stabilising electricity grids in closed grids in rural areas. This category is also where the majority of actual WH systems have been developed. Third, WH systems to support transportation, which, based on this literature review, seems to be an emerging sector in the hydrogen industry. In all three categories, the reviewed studies showed the benefits of the implementation of WH systems in the electricity production by reducing GHG emissions, while introduction of commercialised FC vehicles fuelled by hydrogen produced by this kind of systems would decrease further the $CO_2$ released by conventional vehicles. Nevertheless, the expansion of hydrogen usage for all three categories has to be supported by a continuous development of the technology. One important academic parameter was recently highlighted, namely the need for emphasizing the focus on energy-exergy analyses for integrated power systems consisting of a renewable energy system, and hydrogen as a storage carrier (Khosravi et al., 2018). Based on the review of this paper, it becomes clear that future studies should specify the energy-exergy analysis on specific combinations of wind turbines and hydrogen systems to ensure a sound development.

The analysis of literature trends discovered that the three main categories are supported by three configurations, namely 1) electrolysis; 2) electrolysis and storage; and 3) electrolysis, storage and FCs. The trend revealed in this study indicates that the studies focus less on hydrogen as a storage application for wind power and more on hydrogen as a multifunctional ancillary service or add-on to the wind farm with multiple outputs and configurations. This trend is based on the increasing demand for hydrogen for transportation, as well as the low efficiency and uncertainty of FC performance. The overall development is expected to continue, both in industry and academia, as the trend in the past decades indicated more studies conducted on WH systems with greater incentives of combining the two technologies.

## 4.2 Optimisation of a hydrogen production – storage – re-powering system participating in electricity and transportation markets. A case study for Denmark

The power capacity of renewable energy sources is constantly increasing through the installation of new units, primarily comprising the most mature technologies such as wind and solar energy converters, as well as through the implementation of innovative technologies that are currently at an infant stage of development. The aim of this study was to investigate the prospects of implementing hydrogen technologies in the electricity network as an electricity production unit or/and utilise the produced hydrogen as transportation fuel. Three main scenarios were identified to be the most appropriate for this: 1) Support of the electrical grid via a fuel cell; 2) participation of a hydrogen production and fuel cell system in the electricity and transportation markets; and 3) participation in the transportation market.

The results indicated that a fuel cell generator providing ancillary services is not economically viable in the investigated case study, while implementing a hydrogen production unit with a hydrogen fuel selling price between 4 and 114 €/kg$H_2$, depending on the electrolyser's power input, will yield positive results. For the third scenario, the hydrogen fuel price ranged between 3.6 and 15.0 €/kg$H_2$. This research shows that hydrogen technologies can be used in the electricity and transportation markets from a technical point of view. However, from an economic point of view, a hydrogen system used only for a single application does not seem to be financially appealing. This suggests that reducing the investment cost and/or limiting operating costs is mandatory to support this type of investment.

### 4.2.1 Introduction

The Danish electricity network is divided into two parts: DK1 and DK2 representing the grids covering Jutland and Funen as well as Zealand and the islands, respectively. DK1 has a higher capacity network with a high RES share, which sometimes leads to network problems such as frequency fluctuations (Aziz and Huda, 2019). The day-ahead electricity market operation in Denmark (part of Nord Pool) also includes the cross-border electricity flows between the Nordic countries, which are used for pricing based on bids and offers from electricity producers/consumers. Consumers and producers, who want to buy and sell electricity, respectively, send their bids and offers one day before the energy is delivered to the network in the spot market (Houmøller, 2017). The aim of Nord Pool is to reduce the price differences between the participating regions and enable better energy planning between the respective TSOs (Unger et al., 2018). However, in some cases, the energy demand cannot be entirely met, which may create frequency imbalances, and as a result, the respective TSO is forced to request power to be added or deducted in the electricity real-time market (Energinet, 2019; Unger et al., 2018). The imbalance between supply and demand often imposes negative prices on electricity, which means that the producers have to pay to dispose their produced electricity.

Fig. 4.2.1 shows the balance of electricity imports/exports for DK1 in 2018 compared to wind energy production and gross consumption. From Fig. 1.3, it is apparent that electricity is exported during high wind power generation, whereas electricity is imported during low wind power generation.

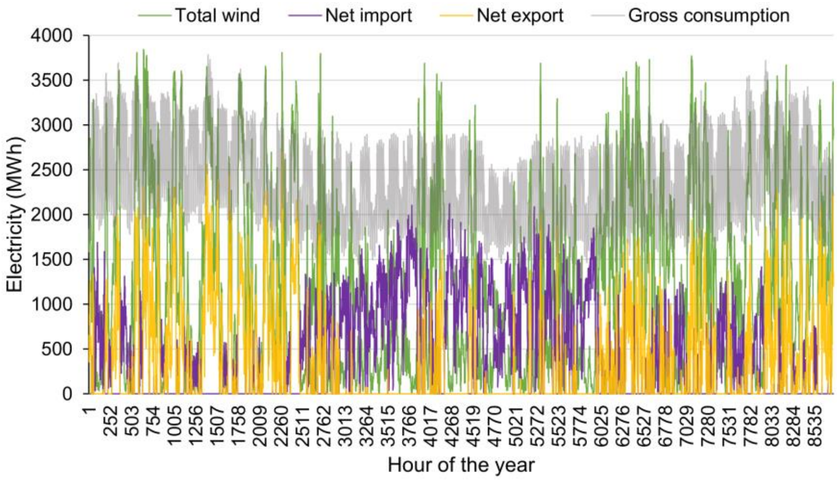



Fig. 4.2.1. Wind energy generation, gross consumption and electricity imports/exports for DK1 in 2018. Based on (Energinet, 2019).

According to the Danish TSO (i.e. '*Energinet*'), the wind energy production exceeds the country's electricity demand many times during a year, and thus the cross-border interconnections are mainly utilised to overcome RES curtailments (see Fig. 4.2.1) (Energinet, 2019). To this end, excess wind energy production is integrated in the system through the electrical interconnections, resulting in negligible levels of wind curtailment. However, it is expected that, at some point, due to a continuous increase of the wind power capacity, there will be bottlenecks in the interconnections between Denmark and the neighbouring countries that will induce wind curtailments. In support of the above, a research published by Lindboe et al. (2015) on behalf of the Danish TSO indicated that by 2040, wind power curtailments in Denmark may increase significantly compared to today. Curtailments are forecasted to present an increasing trend from 0.75% in the optimistic scenario (including the deployment of a new 'Viking Link' interconnector, large heat pumps and flexibility of larger power plants) to 3.25% in the base scenario (without the 'Viking Link' and development of power systems similar to the IEA new policy scenario) (Lindboe et al., 2015).

Acknowledging the above, it is obvious that apart from upgrading the contemporary transmission interconnection system in Denmark, it would be highly advantageous to integrate energy storage systems that allow higher RES capacities and contribute to reaching the 2050 goal of fossil fuel independence (Danish Energy Agency, 2016).

Energy storage is a concept that has been studied extensively in recent decades. It includes different technologies that can be coupled with RES (e.g. wind power), and depending on the application, the produced energy is stored for later use.

Based on a report published by IEA in 2019, hydrogen is versatile, because, on the one hand, it can be produced from different sources (e.g. fossil fuels, RES and nuclear power), and, on the other hand, it can be used in many applications such as electrical power support, transportation fuel and heat generation in the building sector (IEA, 2019c). For many years, research has focused on studying the prospects of hydrogen technologies mainly for RES storage or as transportation fuel. Another significant aspect of hydrogen technologies is the use of hydrogen as a bi-product, both in support of the electricity network and as fuel for 'green' mobility or other applications (Apostolou and Enevoldsen, 2019). In this context, several studies in peer-reviewed literature analyse hydrogen systems either for re-electrification or for both electrical network support and transportation. However, none of these studies has provided a tool that could optimise the operation of a hydrogen system used in both applications, taking into account electricity market prices and investment opportunities for future investors.

González et al. (2004) developed an optimisation and simulation algorithm for a hybrid wind power system/hydrogen system to promote the penetration of wind energy in Ireland. The results showed a minimisation of wind energy surplus of 7.5% of the initial value by incorporating a 30 MW electrolyser. The produced hydrogen was calculated to supply fuel to approximately 541,000 vehicles, while the annual avoided emission from the increased wind power penetration and 'green' transportation was estimated to 10 Mt (González et al., 2004). In the same context, Schenk et al. (2007) investigated the prospects of a hydrogen system to increase wind power integration in the Netherlands. The grid-connected system was found to assist the electricity network in cases of heavy loads during high wind energy production by absorbing the excess energy for producing the hydrogen gas (Schenk et al., 2007).

Researchers aiming to find solutions for energy security and lower GHG emissions are examining the implementation of hydrogen systems in smaller grids, e.g. on islands. Antoine et al. (2008) studied the prospects of high RES integration in Malta, including a hydrogen conversion and storage system able to support the grid and provide hydrogen fuel in the transportation sector. The scenario indicated that the net effect of the FC energy supplied to the grid was insignificant; however, the system was used to absorb the excess RES hydrogen production after meeting 5% of the transportation fuel demand (Antoine et al., 2008). Similarly, Kavadias et al. (2018) examined the utilisation of hydrogen production from excess RES energy in an autonomous island grid to support the grid or as a fuel for light-duty transportation. The results showed that the produced hydrogen could be used to reduce the oil-based generation during peak power demands. In addition, the results showed that approximately 260 FC scooters could operate on a daily basis, resulting in lower GHG emissions and lower fuel costs compared to conventional counterparts (Kavadias et al., 2018).

Salgi et al. (2008) investigated the prospects of producing hydrogen in western Denmark for transport applications based solely on the electricity market prices and a forecasted wind power production for 2030. The developed simulation model showed that even without hydrogen storage constraints, only 32% of the assumed hydrogen demand in 2030 could be covered if electrolysers would operate at a maximum bid price of 20 €/kWh (Salgi et al., 2008).

Likewise, Carr et al. (2016) assessed the operation of an on-site hydrogen production refuelling station powered from a wind turbine connected to the electrical grid in Rotherham, UK. Optimising the system to maximise the revenues (i.e. electricity sales) while at the same time minimising the operating costs (i.e. electricity costs) showed that electricity prices and hydrogen demand play a significant role in the system's economic viability. However, the hydrogen fuel sales were not taken into consideration, limiting the hydrogen demand, which in case of higher values would compromise the economic viability of the project due to increased hydrogen production and less available wind energy to be sold into the electrical grid (Carr et al., 2016).

In their research, Hou et al. (2017) presented various cases of hydrogen systems' integration in the Danish energy and transportation sector. Offshore wind power-generated hydrogen was initially examined as a fuel for re-electrification via a FC with hydrogen produced from off-peak electricity, while the FC-generated electricity was sold to the grid at high market prices. The results indicated that this scenario was not optimal from an economic point of view due to the low number of high price differentials in the market. However, using the produced hydrogen as transportation fuel, the scenario resulted in electrolyser capacities of 13.5 and 23.4 MW with a hydrogen fuel cost of 5 and 9 €/kg$H_2$ and a payback period of 5.5. and 2.6 years, respectively (Hou et al., 2017).

#### 4.2.1.1 Aims and objectives

The scope of this research was to assess the prospects of hydrogen systems participating in the electricity and/or other applicable markets from an investor's perspective. The ongoing transition to higher shares of RES in the electricity networks mandates the use of energy storage systems capable of coping with the grid problems arising from the dynamic output of renewable power generation. Moving towards a non-fossil fuel era, new methods for achieving this goal will include technologies that have the ability to present multiple end-uses to reduce costs and support sustainability.

In this context, according to Apostolou and Xydis (2019), the transportation sector is one of the most significant sectors requiring decarbonisation (Apostolou and Xydis, 2019). EU statistics show that following the energy industry, the transportation industry was the second largest GHG contributor, accounting 27% of the total GHG emissions in 2017, of which more than 71% was directly linked to road vehicles (European Commission, 2020b). Today, there are two commercialised vehicle technologies with zero direct $CO_2$ emissions. These are the BEVs and the FCEVs. Although the latter still represents a low number of entities, their prospects seem positive compared to BEVs in terms of higher driving autonomy and faster refuelling times (Apostolou and Xydis, 2019). The main issue with FCEVs is the lack of infrastructure and the fact that most hydrogen fuel is produced from fossil fuels (Nikolaidis and Poullikkas, 2017). Hence, although FCEVs are considered emission-free vehicles, the hydrogen fuel production is a GHG emission-intensive process (e.g. steam-methane reforming), limiting the ‘green’ character of the vehicle.

To this end, the main objective of this study was to develop a novel algorithm for investigating various scenarios regarding the sizing and optimisation of hydrogen systems that provide support on a grid with substantial RES capacity and/or ‘green’ hydrogen fuel for transportation, while offering an economically feasible business case for future stakeholders. Hence, the above-mentioned objectives can be described by the following RQs:

- Is it possible to size hydrogen systems participating in the electricity and/or the transportation market accordingly to be economically viable?
- Which of the two markets comprises the most promising in terms of an investment?

### 4.2.2 Methodology

The investigation of the stated RQs was based on the mathematical formulation of a model, including water electrolysis, FC operation and an economic evaluating tool used for three scenarios regarding the utilisation of a hydrogen-based system in the electricity and/or transportation markets. As described previously, the Danish electricity market DK1 was selected as a case study because of its specific characteristics of the electricity network and the market in general. The developed model has been applied to all three scenarios for the period between 2014 and 2018 in order to assess a future trend of economic parameters such as investment and hydrogen fuel costs.

The examined SCs covering basic configurations of hydrogen systems participating in electricity markets included:

- SC4.1: A PEM FC system supplied with hydrogen purchased from an external supplier participated in the spot and real-time markets. SC4.1 did not incorporate a hydrogen production-storage unit to supply the FC with hydrogen due to the cost ratio between fossil fuel- and RES-based production, which in literature currently ranges between 1/4 and 1/2 (Apostolou and Enevoldsen, 2019; IEA, 2019c). Thus, when implementing a system that also includes a hydrogen production and storage facility, a negative financial result is expected to deteriorate.

- SC4.2: A hydrogen system participated in the electricity and transportation markets with a priority on the electricity markets. Compared to SC4.1, this scenario involved the production, storage and utilisation of the hydrogen produced for re-electrification and the remaining gas as a 'green' fuel for transportation. In the event of no participation in the transportation market, SC4.2 would correspond to SC4.1 with an internal supply of hydrogen to the FC. SC4.2 consisted of two cases: SC4.2a with continuous operation of the electrolyser and SC4.2b with operation only during periods of excess wind energy ($P_{exwind}>0$), i.e. when the wind energy production was higher than the total demand.

- SC4.3: The hydrogen system included hydrogen production and storage facilities that participated in the electricity markets as a consumer and distributed the produced hydrogen for 'green' transportation purposes only. Like SC4.2, SC4.3 consisted of two cases: SC4.3a with continuous operation of the electrolyser and SC4.3b with operation only during periods of excess wind energy.

#### 4.2.2.1 Model development

A hydrogen-based system able to participate in the electricity and/or the fuel transportation markets comprises of different components. There are three main sections of such a system consisting of a hydrogen production unit (in this case a water electrolysis system with a rated power ($P_{max}$), a hydrogen gas storage unit and a FC ($P_{FC}$) for utilisation in the repowering sector. To this end, the development of the model was divided into the three aforementioned SCs, which were combined based on the requirements of each SC.

The algorithm presented in Fig. 4.2.2 indicates that depending on the SC, the water electrolysis system participates as a consumer in the spot and the real-time markets based on the following day's lowest price given by the TSO. Additionally, participation in the real-time market only occurs when there is a surplus power ($P_{surplus}$) in the system. Similarly, the FC generator participates in the spot and real-time markets, but as a producer. In the event of a power deficit ($P_{def}$) in the grid and the hourly price given by the TSO is positive for participating in the real-time market ($Price_{bal}$), the FC generator participates in the real-time market. If there is no deficit and the spot hourly price ($Price_{sp}$) is positive, the FC generator participates in the spot market. In all other cases, there is no participation of the FC generator in the markets and the produced hydrogen is available in the transportation market.

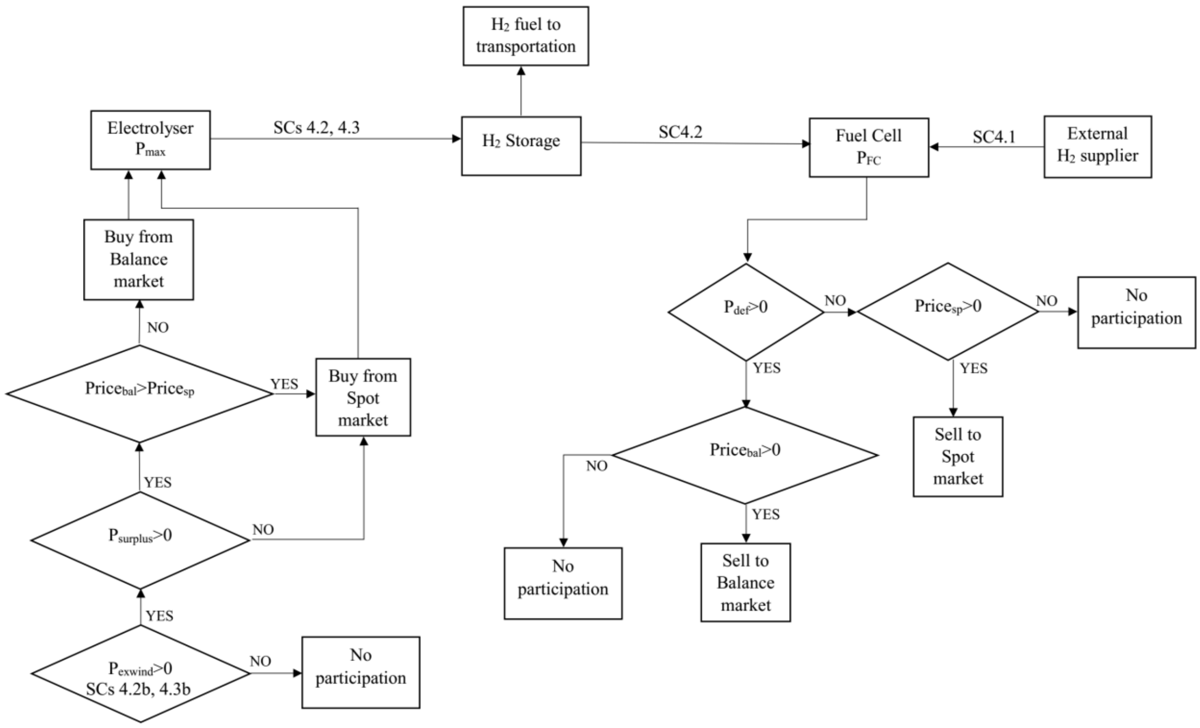



Fig. 4.2.2. Algorithm used for the determination of the system's operation in the corresponding markets based on the examined SC.

#### 4.2.2.1.1. Water electrolysis model

The developed model for describing the water electrolysis process was based on the results from (Apostolou et al., 2019; Diéguez et al., 2008; Kavadias et al., 2018; Ulleberg, 2003), outlining the thermodynamic, mass and thermal processes of alkaline water electrolysis. The main Eqs. used for the model development are:

$$U_{rev} = U_{rev,T,P^0} - \frac{R \ T_{el}}{z \ F} \ ln\left(\frac{a_{H2O}}{a_{H2} \ a_{O2}{}^{1/2}}\right) \quad (4.2.1)$$

$$U_{cell} = U_{rev} + \left(\frac{r1+r2 \quad T_{el}}{A}\right) \ I + \left(s_1 + s_2 T_{el} + s_3 T_{el}{}^2\right) \quad log\left[\left(\frac{t1+\frac{t2}{T_{el}}+\frac{t3}{T_{el}{}^2}}{A}\right) \ I + 1\right] \quad (4.2.2)$$

$$\eta_F = \left( \frac{\left(\frac{I}{A}\right)^2}{f_1 + \left(\frac{I}{A}\right)^2} \right) \; f_2 \tag{4.2.3}$$

$$\dot{n}_{H2} = \eta_F \left( \frac{n_c \;\; I}{z \;\; F} \right) \tag{4.2.4}$$

$$C_t \frac{dT}{dt} = \quad \dot{Q}gen - \dot{Q}loss - \dot{Q}cool - \dot{Q}sens \tag{4.2.5}$$

where $U_{rev}$ is the reversible voltage in V, $U_{rev,T,P}{}^{o}$ is the reversible voltage under standard conditions in V, $R$ is the universal gas constant and $F$ is the Faraday constant. $T_{el}$ is the operational temperature in °C and $\alpha_{H2}$, $\alpha_{O2}$, $\alpha_{H2O}$ are the activity coefficients of hydrogen, oxygen and water in kg, respectively. $I$ is the water electrolysis current in A, $A$ is the surface of the electrodes, $r_1$, $r_2$ represent ohmic parameters, $s_1$, $s_2$, $s_3$ and $t_1$, $t_2$, $t_3$ account for the overvoltage parameters of the anode and cathode, respectively. $\eta_F$ is the Faraday efficiency and $f_1$, $f_2$ are the Faraday parameters. $\dot{n}_{H2}$ is the hydrogen production rate, $z$ is the number of electrons required to split each molecule of water and $n_c$ is the number of electrolytic cells.

Eq. 4.2.5 describes the thermal balance during the electrolysis process, where $C_t$ is the total thermal capacity of the electrolyser, $\dot{Q}_{gen}$ is the generated heat in W and $\dot{Q}_{loss}$ is the heat loss transfer to the environment. $\dot{Q}_{gen}$ is a function of thermoneutral voltage ($U_{tn}$), which depends on the operating temperature (see Eq. 4.1.6), while $\dot{Q}_{loss}$ depends on the ambient temperature, which is considered to be constant due to the assumption of an indoor installation (see Eq. 4.1.7). $\dot{Q}_{cool}$ equals to the heat removed via the cooling system (see Eq. 4.1.8). $\dot{Q}_{sens}$ represents the enthalpy leaving the system with the product streams along with the heat transferred from the unit to the input water (see Eq. 4.1.9) (Apostolou et al., 2019; Kavadias et al., 2018).

$$\dot{Q}gen = I \quad n_c \;\; (U_{cell} - U_{tn}) \tag{4.2.6}$$

$$\dot{Q}loss = \frac{1}{R_t} \quad (T_{el} - T_a) \tag{4.2.7}$$

$$\dot{Q}cool = C_{CW} \quad \left(T_{CW,in} - T_{CW,out}\right) \tag{4.2.8}$$

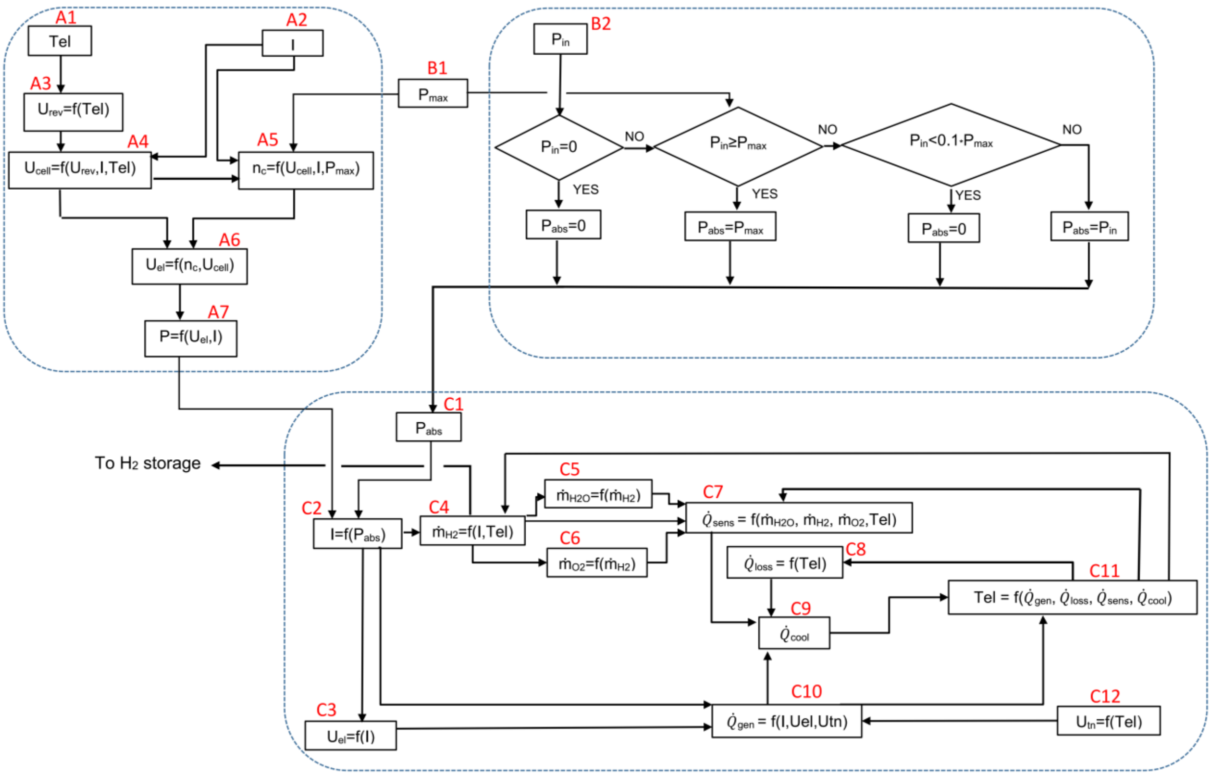
$$\dot{Q}sens = (\dot{m}_{H2} \;\; c_{H2})(T_{el} - T_a) + (\dot{m}_{O2} \;\; c_{O2})(T_{el} - T_a) + (\dot{m}_{H2O} \;\; c_{H2O})(T_{el} - T_{H2Oi}) \tag{4.2.9}$$

where $R_t$ is the total thermal resistance of the electrolyser, $T_a$ is the ambient temperature, $m_{H2}$, $m_{O2}$, $m_{H2O}$ are the mass flow rates of the hydrogen, oxygen and inlet water, respectively, in kg/s and $c_{H2}$, $c_{O2}$, $c_w$ are the specific thermal capacities of the hydrogen, oxygen and inlet water in J/kgK. $T_{H2Oi}$ is the temperature of the entering water, $C_{cw}$ is the thermal capacity of the cooling water in J/K, $T_{cw,in}$ is the inlet temperature of the cooling water and $T_{cw,out}$ is the outlet temperature of the cooling water (Kavadias et al., 2018).

The electrolytic cell parameters used during the water electrolysis simulation are presented in Table 4.2.1. The algorithm for calculating the hydrogen-generated quantity based on the rated power of the electrolyser and the input power (e.g. in case of using intermittent wind energy) is depicted in Fig. 4.2.3.

Table 4.2.1. Water electrolysis cell parameters used during the model development (Apostolou, 2015).

| **Electrolytic cell parameters** | | | |
|---|---|---|---|
| **Parameter** | **Symbol** | **Value** | **Units** |
| Electrode's surface | A | 0.25 | $m^2$ |
| Cell's thermal resistance | $R_t$ | 0.008 | K/W |
| Cell's heat capacity | $C_t$ | $2.98\ 10^{-4}$ | J/˚C |
| Empirical ohmic parameter 1 | $r_1$ | $7.3\ 10^{-5}$ | $\Omega\ m^2$ |
| Empirical ohmic parameter 2 | $r_2$ | $-1.1\ 10^{-7}$ | $\Omega\ m^2$/˚C |
| Cathode overvoltage parameter 1 | $t_1$ | $1.6\ 10^{-2}$ | $m^2$/A |
| Cathode overvoltage parameter 2 | $t_2$ | -1.3 | $m^2$ ˚C/A |
| Cathode overvoltage parameter 3 | $t_3$ | 412 | $m^2$ ˚$C^2$/A |
| Anode overvoltage parameter 1 | $s_1$ | $1.6\ 10^{-1}$ | V |
| Anode overvoltage parameter 2 | $s_2$ | $1.38\ 10^{-3}$ | V / ˚C |
| Anode overvoltage parameter 3 | $s_3$ | $-1.6\ 10^{-5}$ | V / ˚$C^2$ |



| | |
|---|---|
| A1: Electrolysis temperature interval set between 20°C and 80°C with a step of 10°C. | C3: Calculation of the electrolysis voltage for the corresponding absorbed power. |
| A2: Electrolysis current interval set between 0 A and 720 A with a step of 40 A. | C4: Flow rate of produced hydrogen. |
| A3: Calculation of the electrolytic cell reversible voltage based on the set temperature. | C5: Flow rate of water consumption. |
| A4: Electrolytic cell voltage. | C6: Flow rate of oxygen production. |
| A5: Number of electrolytic cells based on the electrolysis rated power. | C7: Calculation of sensible heat. |
| A6: Electrolysis stack voltage. | C8: Calculation of heat losses. |
| A7: Equations of electrolysis input power and electrolysis current at different temperatures. | C9: Heat removed through the cooling system. |
| B1: Rated power of the electrolyser. | C10: Electrolysis generated heat. |
| B2: Available power input to electrolyser. | C11: Electrolysis operating temperature. |
| C1: Absorbed power by the electrolyser. | C12: Thermoneutral volatage. |
| C2: Calculation of the electrolysis current for the corresponding absorbed power. | |

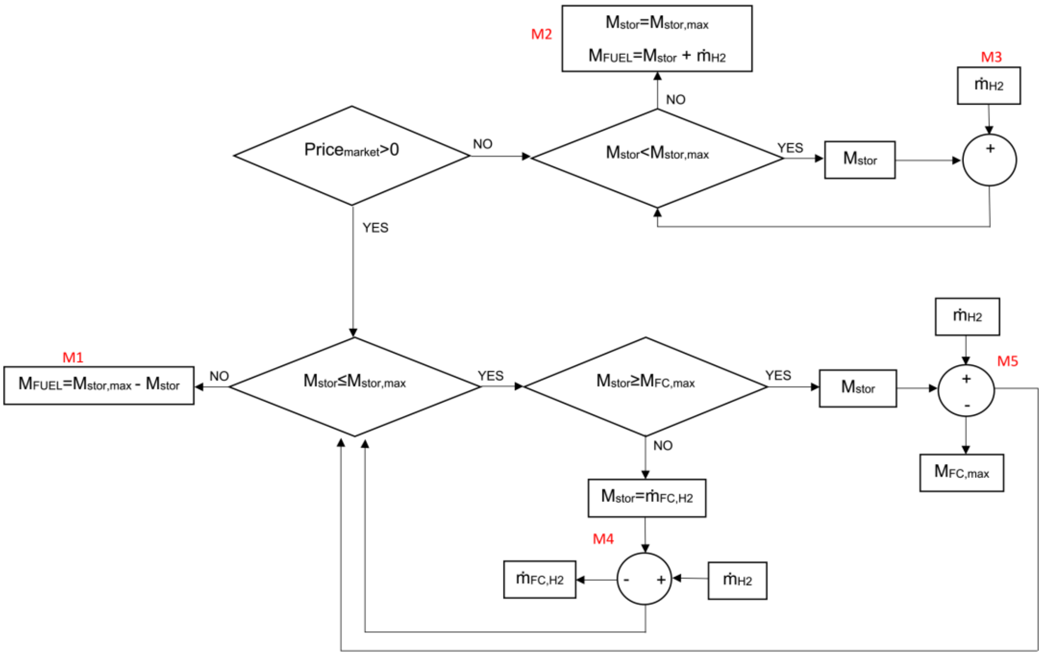
Fig. 4.2.3. Water electrolysis algorithm. Based on (Apostolou et al., 2019; Kavadias et al., 2018).

This algorithm can be divided into three main sections (see Fig. 4.2.3). The upper left determines the relationship of the electrolysis power input, current and voltage ($U_{el}$) at different operating temperatures set between 20 and 80°C. The upper right section calculates the absorbed power ($P_{abs}$) by the electrolyser (i.e. mainly in case of intermittent operation) based on the input power ($P_{in}$), while the lower part describes the electrolysis processes and the calculation of the hydrogen quantity produced during the operation of the system (Kavadias et al., 2018).

#### 4.2.2.1.2. Hydrogen storage model

The hydrogen produced during the electrolysis process leaves the electrolyser at a pressure of 3 MPa. However, hydrogen storage and transportation to end-users usually occur under higher pressures, though not exceeding 20 MPa, to minimise operating costs and use of simpler materials (Andersson and Grönkvist, 2019). Therefore, after storing the hydrogen in the storage tanks, the produced hydrogen is compressed by a hydrogen compressor before transportation to hydrogen consumers. SC4.1 does not take into account the hydrogen storage configuration, because hydrogen gas is assumed to be delivered by an external supplier. Additionally, in SC4.3, the total hydrogen produced is sold to the transportation market, and thus, the hydrogen tank plays a buffer role, and its capacity is taken to be equal to the maximum daily hydrogen mass production.

Based on the above, the algorithm for calculating the hydrogen mass flow to and from the hydrogen storage tank corresponds to SCs 4.2 and 4.3 and is shown in Fig. 4.2.4.




| | |
|---|---|
| M1: In case hydrogen mass in the storage tank exceeds maximum capacity, the excess hydrogen is availble for transportation purposes. | M4: Hydrogen flow rate from storage tank to the fuel cell equals to the hydrogen stored in the storage tank at the specific time. Subsequently, hydrogen mass in the storage tank is calculated by adding electrolysis hydrogen production. |
| M2: In case hydrogen mass in the storage tank exceeds maximum capacity, all available hydrogen is available for transportation purposes. | M5: If hydrogen stored in the storage tank is more than the one the fuel cell requires for operating at rated power, then hydrogen mass in the storage tank is calculated by adding electrolysis hydrogen production and substracting hydrogen consumed by the fuel cell. |
| M3: Hydrogen production flow rate from the electrolysis process. | |

Fig. 4.2.4. Algorithm for calculating the hydrogen mass stored in the storage tank, transferred to the FC and being available for transportation.

According to Fig. 4.2.4, the hydrogen mass flow algorithm was based on the electricity prices in the markets in which the FC generator participated (i.e. the spot and real-time markets). In the case of positive prices, the hydrogen mass stored in the storage tank ($M_{stor}$) equals to the hydrogen produced by the electrolyser ($\dot{m}_{H2}$) minus the hydrogen supplied to the FC ($\dot{m}_{FC,H2}$), while in the case of negative prices, the produced hydrogen is used only for transportation ($M_{FUEL}$). In the first case, the excess hydrogen that cannot be stored in the storage facility is again available as transportation fuel. The capacity of the hydrogen storage tank ($M_{stor,max}$) is assumed to be equal to the maximum daily hydrogen production of the electrolyser, and the maximum hydrogen mass consumption of the FC ($M_{FC,max}$) is calculated according to the rated power of the FC ($P_{FC}$).

#### 4.2.2.1.3. The fuel cell model

The modelling of the FC was based on two sub-models comprising the electrochemical and the thermal models. According to (Al-Baghdadi, 2005) as well as (Chavan and Talange, 2017), and assuming that hydrogen fuel utilisation in the FC is equal to one, the FC output current can be calculated as:

$$I_{FC} = \frac{\dot{m}_{FC,H2} \quad z \quad F}{n_{cFC} \quad MW_{H2}} \tag{4.2.10}$$

where $\dot{m}_{FC,H2}$ is in kg/s, $z$ is the number of electrons in the reaction per hydrogen molecule (=2), $F$ is the Faraday's constant, $n_{cFC}$ is the number of FCs and $MW_{H2}$ is the molecular weight of hydrogen in kg/mol.

The cell voltage of the FC ($U_{FCcell}$) in V can be described as a function of the FC's reversible voltage ($U_{revFC}$) and the different overpotentials observed during the operation of a FC. The FC's cell voltage can therefore be expressed as (Benchouia et al., 2013; Berning and Djilali, 2003):

$$U_{FCcell} = U_{revFC} - U_{act} - U_{ohm} - U_{diff} \tag{4.2.11}$$

where $U_{act}$ is the activation overpotential describing the voltage drop observed during the transfer reaction between the electrode and electrolyte interface, $U_{ohm}$ describes the voltage drop due to the cell's electrical resistance losses and $U_{diff}$ accounts for the diffusion overpotential resulting from the mass transfer limitations of the reactants.

The FC's reversible voltage can be derived from the Nernst Eq. and is calculated from Eq. 4.2.12 (Benchouia et al., 2013; San Martin et al., 2014).

$$U_{revFC} = 1.229 \quad 10^{-4} \quad (T_{FC} - 298.15) + 4.31 \quad 10^{-5} \quad T_{FC} \quad \ln(p_{H2}/10^5 \sqrt{p_{O2}/10^5}) \tag{4.2.12}$$

where $T_{FC}$ is the FC's operating temperature in K and $p_{H2}$, $p_{O2}$ are the partial pressures of hydrogen and oxygen reactants in Pa. The partial pressures of the reactants can be calculated from Eqs. 4.2.13 and 4.2.14 (Al-Baghdadi, 2005).

$$p_{H2} = \frac{p_{H2O}^{Sat}}{2} \quad \left( \frac{1}{exp\left(\frac{1.653 \quad i_d}{T_{FC}^{1.334}}\right) X_{H2O}} - 1 \right) \tag{4.2.13}$$

$$p_{O2} = p_{H2O}^{Sat} \quad \left( \frac{1}{exp\left(\frac{4.192 \quad i_d}{T_{FC}^{1.334}}\right) X_{H2O}} - 1 \right) \tag{4.2.14}$$

where $p_{H2O}^{Sat}$ is the saturation pressure of water in Pa and is calculated from Eq. 4.2.15, $i_d$ is the current density in A/cm² and $X_{H2O}$ is the molar fraction of water vapour and is given by Eq. 4.2.16 (Berning and Djilali, 2003).

$$\log_{10}(p_{H2O}^{Sat}/10^5) = -2.1794 + 0.02953 \quad (T_{FC} - 273.15) - 9.1837 \quad 10^{-5} \quad (T_{FC} - 273.15)^2 + 1.4454 \quad 10^{-7} \quad (T_{FC} - 273.15)^3 \tag{4.2.15}$$

$$X_{H2O} = \frac{p_{H2O}^{Sat}}{p_{FC}} \tag{4.2.16}$$

where $p_{FC}$ is the total input pressure in Pa.

The calculation of the activation overpotential is a function of the operating temperature and the current density of the FC. (San Martin et al., 2014) proposed the following formula:

$$U_{act} = \frac{R \quad (T_{FC} - 273.15)}{z \quad a \quad F} \quad \ln \frac{i_d}{i_{do}} \tag{4.2.17}$$

where $a$ represents the exchange coefficient, and is approximately equal to 0.5, and $i_{do}$ is the exchange current density in A/cm² described as: $i_{do}$ = 1.27 $10^{-8}$ exp(2.06 $p_{O2}$) (Berning and Djilali, 2003).

Fowler et al. (2002) and Al-Baghdadi (2005) described the internal resistance of the FC ($R_{int}$) in Ω cm² as a function of temperature and current output of the FC along with the membrane parameters such as resistivity ($r_m$) in Ω cm, surface area ($A_{FC}$) and thickness ($l$). In this context, Eqs. 4.2.18 to 4.2.20 are used to determine the ohmic overpotential (Al-Baghdadi, 2005; Fowler et al., 2002).

$$U_{ohm} = i_d \quad R_{int} \tag{4.2.18}$$

$$R_{int} = \frac{r_m \ l}{A_{FC}} \tag{4.2.19}$$

$$r_m = \frac{181.6\left(1+0.03\left(\frac{i_d}{A_{FC}}\right)+0.062\left(\frac{T_{FC}}{303}\right)^2 \quad \left(\frac{i_d}{A_{FC}}\right)^{2.5}\right)}{\left(14-0.634-3\left(\frac{i_d}{A_{FC}}\right)\right) \quad exp\left(4.18\left(\frac{T_{FC}-303}{T_{FC}}\right)\right)} \tag{4.2.20}$$

The diffusion overpotential occurs because of the lower response of the gas mass flow compared to the load demand alterations and is determined by Eq. 4.2.21 (Al-Baghdadi, 2005; Laurencelle et al., 2001).

$$U_{diff} = m_d \quad exp(n_d \quad i_d) \tag{4.2.21}$$

where $m$ and $n$ are parameters associated with the electrolyte conductivity and the gas diffusion layer porosity, respectively. Laurencelle et al. (2001) estimated the parameters that yielded an average value for $n$ equal to 8 cm² A$^{-1}$, while for the mass transfer coefficient $m$ in V, the authors demonstrated a linear dependence of the operating temperature. Eqs. 4.2.22 and 4.2.23 present the formula used for the estimation of the $m$ parameter for operating temperatures below and above 39°C (Laurencelle et al., 2001).

$$m_d = 3.3 \quad 10^{-3} - 8.2 \quad 10^{-5}(T_{FC} - 273.15), \quad \text{for } T_{FC} < 312.15 \text{ K} \tag{4.2.22}$$

$$m_d = 1.1 \quad 10^{-4} - 1.2 \quad 10^{-6}(T_{FC} - 273.15), \quad \text{for } T_{FC} \geq 312.15 \text{ K} \tag{4.2.23}$$

Taking into account Eqs. 4.2.11 to 4.2.23, one can calculate the power output of the FC ($P_{FCcell}$) based on the input hydrogen fuel by using Eq. 4.2.24.

$$P_{FCcell} = I_{FC} \quad n_{cFC} \quad U_{FCcell} \tag{4.2.24}$$

However, as can be seen from Eqs. 4.2.11 to 4.2.23, the operating temperature of the FC plays an important role in determining $U_{FCcell}$. The operating temperature does not remain constant, and the following thermal model is thus used to calculate the temperature profile during the operation of the system. The proposed thermal model is based on the research of (Laurencelle et al., 2001; San Martin et al., 2014).

The thermal energy balance of the FC system can be described by the formula presented in Eq. 4.2.25.

$$\dot{Q}fc,net = \dot{Q}fc,g - \dot{Q}fc,loss - \dot{Q}fc,cool \tag{4.2.25}$$

where $\dot{Q}_{fc,net}$ is the net heat flow stored in the FC and expressed as a function of temperature (see Eq. 4.2.26). $\dot{Q}_{fc,g}$ is the FC heat flow, which is a function of the heat generated by the reaction ($\dot{Q}_{fc,c}$), the electrical generated power as well as the sensible and latent heat of reactants ($\dot{Q}_{la,se}$) (see Eqs. 4.2.27-4.2.31). $\dot{Q}_{fc,loss}$ represents the heat flow from the system to the environment (see Eq. 4.2.32) and $\dot{Q}_{fc,cool}$ indicates the heat flow removed from the FC's cooling system (see Eq. 4.2.33).

$$\dot{Q}fc,net = C_{t,FC} \quad \frac{dT_{FC}}{dt} \tag{4.2.26}$$

$$\dot{Q}fc,g = \dot{Q}fc,c - P_{FCcell} - \dot{Q}la,se \tag{4.2.27}$$

with

$$\dot{Q}fc,c = \frac{\Delta H_{H2O}}{z \quad F} \quad I_{FC} \quad n_{cFC} \tag{4.2.28}$$

$$\dot{Q}la,se = \sum\left(\dot{m}_{FC,i} \quad c_{p,i} \quad \left((T_{FC} - 273.15) - \left(T_{FC,a} - 273.15\right)\right)\right) + \dot{m}_{FC,H2O} \quad H_{v,H2O}, \tag{4.2.29}$$

$i = H_2,O_2$

$$\dot{m}_{FC,O2} = \frac{1}{2} \quad \frac{MW_{O2}}{MW_{H2}} \quad \dot{m}_{FC,H2} \tag{4.2.30}$$

$$\dot{m}_{FC,H2O} = \frac{MW_{H2O}}{MW_{H2}} \quad \dot{m}_{FC,H2} \tag{4.2.31}$$

$$\dot{Q}fc,loss = \frac{1}{R_{t,FC}} \quad \left((T_{FC} - 273.15) - \left(T_{FC,a} - 273.15\right)\right) \tag{4.2.32}$$

$$\dot{Q}fc,cool = \dot{m}_{cool,H2O} \quad c_{p,H2O} \quad (T_{H2O,in} - T_{H2O,out}) \tag{4.2.33}$$

where $C_{t,FC}$ is the thermal capacity of the FC, $\Delta H_{H2O}$ is the enthalpy of the liquid water formation, $\dot{m}_{FC,i}$ and $c_{p,i}$ are the mass flow rate and the specific heat of the reactants. $T_{FC,a}$ is the FC ambient temperature, $H_{v,H2O}$ is the enthalpy of vaporisation of water and $MW$ represents the molecular weight of the reactants. In Eqs. 4.2.32 and 4.2.33, $R_{t,FC}$ is the thermal resistance of the FC, $\dot{m}_{cool,H2O}$ is the flow rate of the cooling water, and $c_{p,H2O}$ and $T_{H2O}$ are the specific heat and temperature of the cooling water, respectively.

Based on the above-mentioned Eqs., one can calculate the FC temperature evolution according to the following function:

$$C_{T,FC} \quad \frac{dT_{FC}}{dt} = \dot{Q}fc,g - \dot{Q}fc,loss - \dot{Q}fc,cool \tag{4.2.34}$$

The cell parameters used to describe the FC model are presented in Table 4.2.2, while the algorithm developed for simulating the FC operating process is presented in Fig. 4.2.5.

Table 4.2.2. Data used for the development of the FC cell modelling.

| **FC cell parameters** | | | |
|---|---|---|---|
| **Parameter** | **Symbol** | **Value** | **Units** |
| Electrode's surface | $A_{FC}$ | 400 | $cm^2$ |
| Membrane thickness | $l$ | 0.02 | cm |
| Cell's thermal resistance | $R_{t,FC}$ | $6.9\ 10^{-4}$ | K/W |
| Cell's thermal capacity | $C_{t,FC}$ | $1.1\ 10^{3}$ | J/$^o$C |

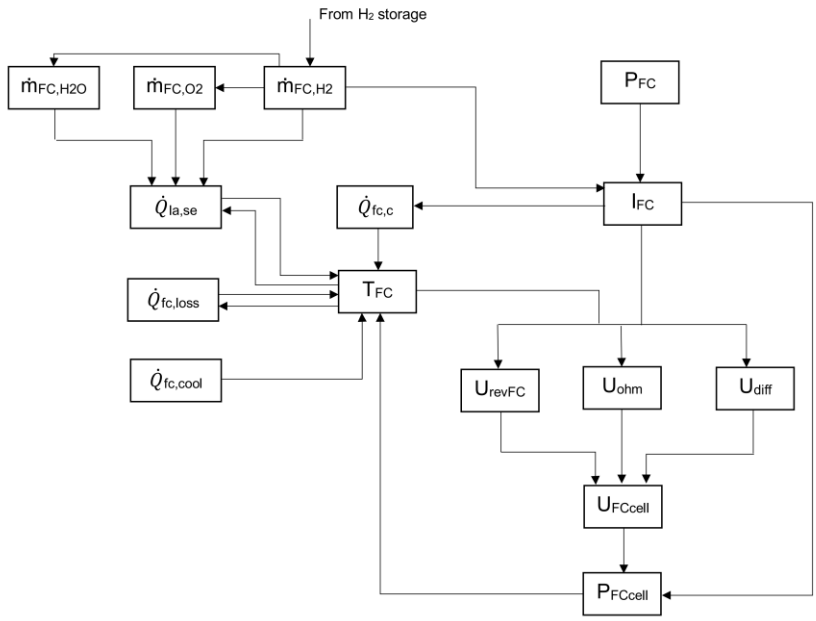



Fig. 4.2.5. Algorithm describing the FC model operation.

As main inputs, the FC algorithm (see Fig. 4.2.5) has the rated power of the FC under investigation and the incoming mass from the hydrogen storage configuration (see Fig. 4.2.4). The output of the FC is not always equal to the rated power of the unit due to various hydrogen input flows and operating temperature fluctuations.

#### 4.2.2.1.4. Financial model

In order to assess the economic viability of such a system in all the investigated scenarios, the NPV and the IRR were introduced to the final algorithm for sizing the system. The calculation of the above parameters was achieved using a set of equations involving the relevant factors of a hydrogen production, storage and repowering system.

Eq. 4.2.35 indicates the calculation of the capital cost ($IC_o$) of such a system (Apostolou et al., 2019; Kuckshinrichs et al., 2016).

$$IC_o = IC_{el}P_{max} + IC_{FC}P_{FC} + IC_{comp} + IC_{H2stor}M_{stror,max} + IC_{constr} \tag{4.2.35}$$

where $IC_{el}$ is the water electrolysis capital cost, $IC_{FC}$ is the capital cost of the FC, $IC_{comp}$ is the cost of the hydrogen compressor, $IC_{H2stor}$ is the hydrogen storage configuration capital cost, $IC_{constr}$ represents the contingency (unexpected) and construction costs ($f_{cost,cont}$ and $f_{cost,constr}$, respectively) as a fraction of the total equipment cost (see Eq. 4.2.36).

$$IC_{constr} = \left(IC_{el}P_{el} + IC_{FC}P_{FC} + IC_{comp} + IC_{H2stor}M_{stror,max}\right)\ \left(f_{cost,constr} + f_{cost,cont}\right) \tag{4.2.36}$$

Table 4.2.3 includes the data used for calculating the system’s investment cost. The capital cost of the electrolysis system corresponds to an average value of the cost range of a 1-MW system documented between 1,000 and 1,500 €/kW (Guerra et al., 2018; Schmidt et al., 2017). In this study, it is assumed that electrolysers above 100 kW of rated power would present a similar cost per kW.

Table 4.2.3. Parameters used for calculating the capital cost of the proposed system.

| Parameter | Symbol | Value | Units | Source |
|---|---|---|---|---|
| Cost of the electrolysis system | $IC_{el}$ | 1,200 | €/kW | (Bertuccioli et al., 2014; Guerra et al., 2018; Schmidt et al., 2017) |
| Cost of the hydrogen tank | $IC_{H2stor}$ | 300 | €/kg$H_2$ | (Mayer et al., 2019) |
| Hydrogen compressor cost | $IC_{comp}$ | 125,000 | € | (Pratt et al., 2015) |
| Cost of the FC system | $IC_{FC}$ | 2,660 | €/kW | (Betalle Memorial Institute, 2017) |
| Construction work parameter | $f_{cost,constr}$ | 0.15 | - | (Gim and Yoon, 2012) |
| Contingency parameter | $f_{cost,constr}$ | 0.08 | - | (Gim and Yoon, 2012) |

The calculation of the NPV was based on assumptions about the operation of the system in terms of its lifetime ($n$ = 20 years) and the required workforce (730 hours per year due to a partially automated system). Other parameters also included bank loans with 30% own capital investment and 70% covered by a loan and a required footprint (in $m^2$, corresponding to the total rated power of the system in kW). In addition to the above, the other data used in Eqs. 4.2.37 and 4.2.38 giving the NPV of the project (Apostolou et al., 2019; Xydis, 2013b) are presented in Table 4.2.4.

$$NPV = \left(\Phi * \sum_{j=1}^{j=n}\left(Tr_j - PO_j - FC_{OMj} - In_j - Rn_j - Ad_j - Iloan_j\right) + \sum_{j=1}^{j=n} Ad_j - \sum_{j=1}^{j=n}\left(Inst_j - LL_j * i\right)\right) * CV_{coef} - IC_o \quad (4.2.37)$$

$$\text{with } CV_{coef} = \frac{1}{(1+r_c)^j} \quad , j = 1 \ \ to \ \ n \quad (4.2.38)$$

where $Tr$ represents the revenues from the sale of hydrogen fuel and the repowering income, $PO$ is the amount of salaries per employee during the operational period $n$, and $FC_{OM}$ is the O&M costs of the system components, including water electrolysis ($OM_{el}$), compressor ($OM_{comp}$), FC configurations and auxiliary equipment (e.g. power electronics) ($OM_{FC}$). A replacement cost of the main electrolyser and the FC parts at the 11th year of operation was added to $FC_{OM}$. $In$ accounts for insurance cost, $Rn$ is the land-lease price per month and $Ad$ is the depreciation. $Iloan$ is the interest of the loan, $Iinst$ is the payment amount of the loan assuming a rate of interest $i$, $LL$ is the remainder of the loan amount and $CV_{coef}$ is the conversion coefficient in current values with $r_c$ being the weighted average cost of capital (Apostolou et al., 2019).

Table 4.2.4. Data used for the calculation of the NPV formula.

| Parameter | Symbol | Value | Units | Source |
|---|---|---|---|---|
| Income tax coefficient | $\Phi$ | 0.22 | - | (Melchior and Mailund, 2018) |
| Labour wage | $PO$ | 33 | €/h | (Statistics Denmark, 2013) |
| Annual electrolyser O&M | $OM_{el}$ | 1.5% $IC_{el}$ | € | (Bechrakis et al., 2006; Bertuccioli et al., 2014) |
| Annual FC O&M | $OM_{FC}$ | 1.0% $IC_{FC}$ | € | (Bechrakis et al., 2006; Bernal-Agustín and Dufo-López, 2008) |
| Annual compressor O&M | $OM_{comp}$ | 4.0% $IC_{comp}$ | € | (Mayer et al., 2019) |
| Replacement cost of stacks | $FC_{OM,st}$ | 30% ($IC_{el}$+$IC_{FC}$) | € | (Weidner et al., 2018) |
| Insurance cost | $In$ | 1.0% $IC_o$ | € | (Katikaneni et al., 2014) |
| Land-lease | $Rn$ | 2 | €/$m^2$ | (Lokaleportalen, 2020; Qadrdan and Shayegan, 2008) |
| Depreciation | $Ad_j$ | 10% ($IC_o$-$Ad_{j-1}$) | € | (Hulten et al., 1981) |
| Loan rate of interest | $i$ | 3.2% | - | (National Bank - Statbank, 2020) |
| Weighted average cost of capital | $r_c$ | 3.0% | - | (BEREC, 2018) |

#### 4.2.2.2 Sizing of the system

The process of sizing the system's main components was based on finding the most economically viable case (i.e. positive NPV and IRR) in all the investigated scenarios. The main assumption followed during this methodology included the use of the same market price data and energy profile of each investigated year during the 20-year period of the project SCs. While not valid in reality, it provided information on the rate of change of the market electricity prices in order to have a feasible business case. Fig. 4.2.6 shows the sizing algorithm of the system depending on the SC investigated.

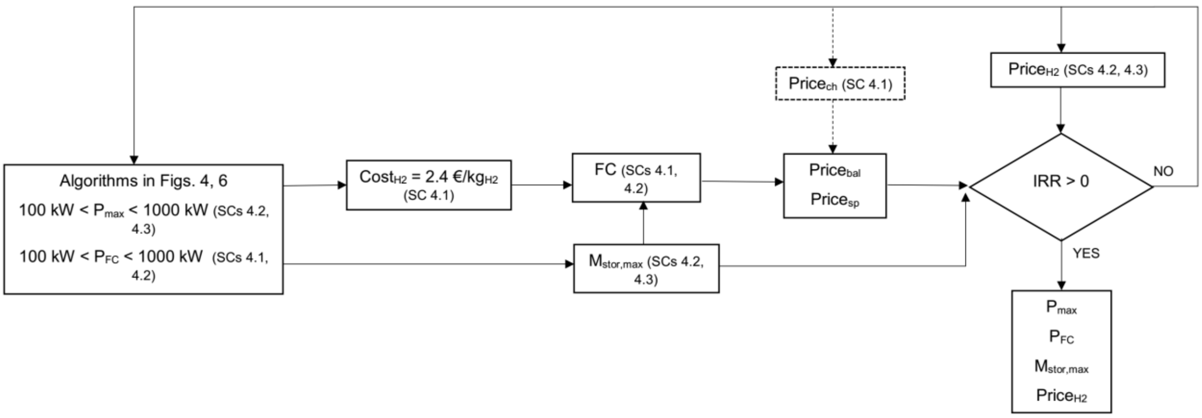



Fig. 4.2.6. Algorithm used to size the hydrogen system and estimate the cost values of hydrogen to be purchased or sold depending on the SC.

In terms of SC4.1, the NPV and IRR based on the electricity prices in the spot and real-time markets between 2014 and 2018 were calculated for a given range of the rated power of a FC. Additionally, the lower range of the hydrogen fuel costs (*$Cost_{H2}$*) for supplying the FC (i.e. 1.5 €/$kgH_2$ production cost for Europe plus 0.9 €/$kgH_2$ for road distribution cost within a range of <200 km assumed to correspond to DK1) (IEA, 2019c) was used to find the respective values of NPV and IRR, where the investment would be economically feasible. However, these costs are rather optimistic and are expected to increase in the future due to carbon taxes and incentives towards 'greener' hydrogen production processes, resulting in a further mitigation of the economic viability of such investments. In case of negative economic parameters (i.e. NPV and IRR), a rate of change factor ($Price_{ch}$) for the $Price_{bal}$ and $Price_{sp}$ values was introduced to determine the change in market prices currently required to obtain a feasible business scenario (see the dot lines in Fig. 4.2.6). However, a possible increase in market prices may not be the most viable solution. To this end, two diminishing factors ($RC_{o,a}$ and $RC_{o,b}$) are introduced in Eqs. 4.2.35 and 4.2.37, respectively, in order to calculate how much the investment ($IC_o$ in Eq. 4.2.35) and O&M ($FC_{OM}$ in Eq. 4.2.37) costs in SC4.1 should be reduced without changing the electricity prices.

SC4.2a and SC4.2b also included the production of hydrogen used for fuelling the FC and the remaining quantity to be used as transportation fuel. Thus, in SC4.2, the introduction of hydrogen fuel costs to be sold to hydrogen consumers ($Price_{H2}$) also consisted of an income variable in the system sizing process. The algorithm depicted in Fig. 4.2.6 is used for estimating the best electrolyser and FC rated power along with the corresponding lowest hydrogen fuel price to have an economically feasible investment.

SC4.3 only included the production of hydrogen through water electrolysis. The hydrogen gas produced was used solely as fuel in the transportation sector. In this case, the sizing of the hydrogen production system was based on a variable hydrogen fuel price for which the NPV and IRR factors present a positive value. In this way, the sizing algorithm's result indicates an economically feasible scenario with the lowest possible hydrogen selling price.

### 4.2.3 Results and discussion

The models/algorithms developed in the previous sections were implemented in the MATLAB software platform as a code able to calculate all the parameters of the respective processes. The input of the scripts depends on the case investigated and can easily be changed to different values of electricity prices, input power to the electrolyser as well as electrolysis and FC stack characteristics. The next sections include the results of the developed methodology for the aforementioned SCs of a hypothetical hydrogen system participating in the Danish electricity and transportation markets. The data used as input for the methodology comprise electricity prices and electrical power values for the years 2014-2018 given by the Danish TSO (see methodology in Section 4.2.2.1).

#### 4.2.3.1 Investigated scenario 4.1

In the first SC, the income of the hydrogen system operation comes solely from participation in the spot and real-time markets as electricity producer. Table 4.2.5 presents the results of the developed model application based on the hourly electricity price data for the years 2014-2018.

Table 4.2.5. Optimisation results of a fuel cell integrated in the electricity markets.

| Parameter | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|
| $P_{FC}$ (kW) | 100 | 100 | 100 | 100 | 100 |
| Electricity produced (MWh) | 800.8 | 799.4 | 801.5 | 796.5 | 799.1 |
| NPV (€) | $-1.56\ 10^6$ | $-1.65\ 10^6$ | $-1.62\ 10^6$ | $-1.56\ 10^6$ | $-1.39\ 10^6$ |
| IRR | - | - | - | - | - |
| Average price of spot market (€/kWh) | 0.031 | 0.023 | 0.027 | 0.030 | 0.044 |
| Average price of real-time market (€/kWh) | 0.034 | 0.026 | 0.029 | 0.033 | 0.046 |

According to Table 4.2.5, it is apparent that in the period investigated, the sizing algorithm outcome was a FC with a lower rated power range, which, however, did not create positive business scenario results (NPV negative). What is obvious though is that as the average electricity prices increase, the NPV increases simultaneously, suggesting that at a certain market price, the business scenario of a FC production unit in the electricity network would be feasible. Although the rated power of the FC in all the investigated years is calculated to be the same, the electricity production is not the same due to different deficit energy and electricity market prices each year (see algorithm in Fig. 4.2.2).

In order to determine what would be the minimum rate for changing the average electricity price in both markets to have an economically feasible business scenario, the sizing algorithm was modified to include a factor of price changes in the electricity market (i.e. $Price_{ch}$ in Fig. 4.2.6). The provided results are presented in Table 4.2.6.

Table 4.2.6. Optimisation of the fuel cell system and calculation of the price change parameter to produce positive economic outcomes.

| **Parameter** | **2014** | **2015** | **2016** | **2017** | **2018** |
|---|---|---|---|---|---|
| $P_{FC}$ (kW) | 750 | 650 | 450 | 800 | 350 |
| Annual operating hours | 8729 | 8714 | 8737 | 8682 | 8711 |
| NPV (€) | $1.68\ 10^4$ | $1.05\ 10^4$ | $2.73\ 10^3$ | $0.88\ 10^3$ | $3.19\ 10^4$ |
| IRR | $1.10\ 10^{-3}$ | $8.21\ 10^{-4}$ | $3.11\ 10^{-4}$ | $5.58\ 10^{-5}$ | $4.70\ 10^{-3}$ |
| $Price_{ch}$ | 340% | 480% | 420% | 340% | 220% |

The results in Table 4.2.6 indicate that the average electricity prices need to be increased by at least 220% to 480% annually in order to have a feasible FC-based producer business scenario. The higher the average electricity price in each market (see Table 4.2.5), the less increase is required to reach economic viability. One may also observe that the sizing algorithm's outcome regarding the rated power of the FC is higher compared to the 100 kW in the business-as-usual scenario (i.e. no electricity market price change). Taking as example the case corresponding to the year of 2018, the algorithm output presented in Fig. 4.2.7 shows that in order to have a feasible business scenario for a FC with a rated power of 100 kW, the average annual market price should change by a factor of at least 3.8 to obtain the least positive NPV. For a 350 kW FC, this factor drops to 3.2. Fig. 4.2.7 also lists all the $Price_{ch}$ factors for the examined FC rated power values.

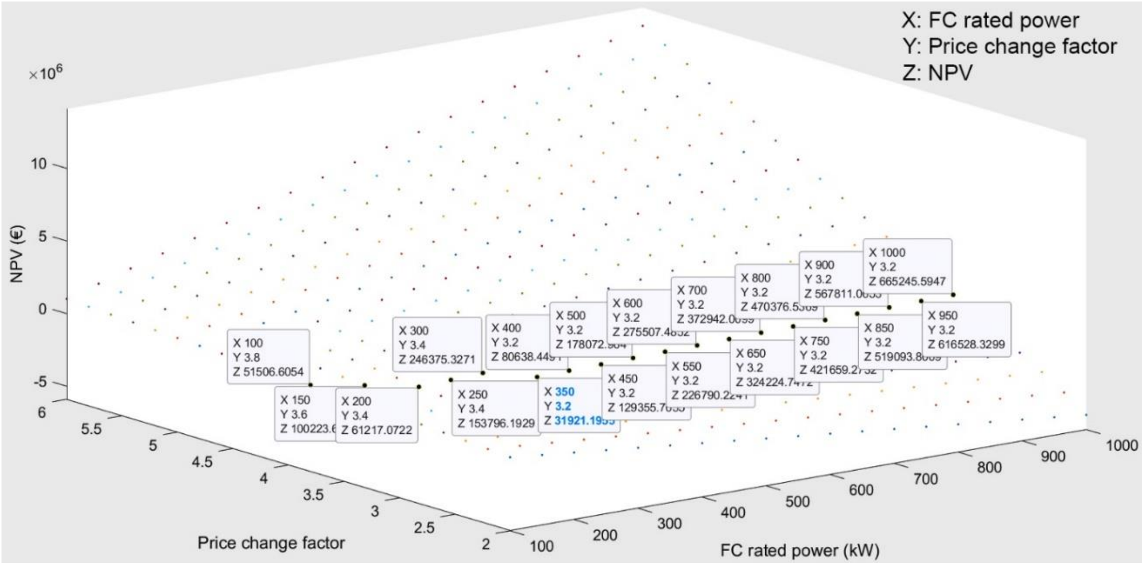



Fig. 4.2.7. Sizing output of the algorithm for the year 2018, including the price change factor and cases where NPV is positive.

The highlighted dots in Fig. 4.2.7 show the lowest $Price_{ch}$ points, where NPV is positive for all the examined FC rated power cases. Obviously, as the FC's rated power increases, the $Price_{ch}$ factor, where NPV turns positive, decreases and vice versa. In other words, the lower $Price_{ch}$ factor, the more the electricity is sold to the market to obtain a higher income, which offsets the increase in investment cost and leads to lower electricity market prices.

However, a significant increase in electricity prices does not seem to be a viable option, and it is rather interesting to note how the investment and O&M costs need to be changed to have an economically viable SC without changing electricity market prices. Table 4.2.7 presents the updated data of Table 4.2.5 with the introduction of the diminishing factors described in Section 4.2.2.2 on the investment and O&M costs.

Table 4.2.7. Optimisation of the fuel cell system and calculation of the diminishing factors of investment and O&M costs to produce positive economic outcomes.

| Parameter | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|
| $P_{FC}$ (kW) | 1000 | 900 | 900 | 1000 | 500 |
| Electricity produced (MWh) | $8.01\ 10^3$ | $7.19\ 10^3$ | $7.21\ 10^3$ | $7.96\ 10^3$ | $3.99\ 10^3$ |
| $RC_{o,a}$ | 0.4 | 0.2 | 0.3 | 0.4 | 0.2 |
| $RC_{o,b}$ | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 |
| NPV (€) | $2.47\ 10^4$ | $2.81\ 10^4$ | $2.98\ 10^4$ | $8.56\ 10^3$ | $1.07\ 10^4$ |
| IRR | $3.20\ 10^{-3}$ | $8.20\ 10^{-3}$ | $6.10\ 10^{-3}$ | $1.10\ 10^{-3}$ | $5.90\ 10^{-3}$ |

According to the results presented in Table 4.2.7, the cost reduction of a hydrogen system participating in the Danish electricity market in order to be economically viable is currently unrealistic. However, such long-term cost reductions should not be entirely rejected; they can be achieved as economies of scale grow. The developed algorithm calculated for all cases a FC rated power at the upper power range showing that when associated costs decrease to levels that allow for profit, large-scale systems are in favour of adequately supporting the electrical grid.

### 4.2.3.2 Investigated scenario 4.2

The second SC is divided into two different sub-categories concerning the operation of the water electrolysis system. The first (SC4.2a) includes a continuous operation of the electrolyser, while the second (SC4.2b) indicates operation of the electrolysis system only during periods of excess wind energy production. The algorithm for SC4.2 sets firstly as priority for the produced hydrogen the support of the grid via a FC and secondly, provision of the remaining fuel to transportation.

#### 4.2.3.2.1. Scenario 4.2a

The algorithm depicted in Fig. 4.2.6 in conjunction with the respective algorithms presented in the previous sections of this paper provides the results of the rated power of the hydrogen production unit, the hydrogen storage configuration and the FC system. The results for the continuous production of hydrogen via the water electrolysis system in all the investigated years are included in Table 4.2.8. The $Price_{H2}$ corresponds to the hydrogen selling price prior to distribution to the final consumers in the transportation sector (e.g. refuelling stations) and is calculated accordingly to give an economically viable investment. If $M_{FUEL}$ is set to zero (i.e. no hydrogen sold for transportation), the result will be a negative IRR, corresponding to SC4.1 with hydrogen supply from an electrolysis-storage system instead of from an external supplier. In comparison with the 2018 NPV results in Table 4.2.5, Table 4.2.8 also includes results for 2018 (column '2018 b') in the case of no participation in the transportation market.

Table 4.2.8. Optimisation results showing the best cases of integrating a hydrogen system with continuous operation in the electricity and transportation markets.

| **Parameter** | **2014** | **2015** | **2016** | **2017** | **2018** | **2018 b** |
|---|---|---|---|---|---|---|
| $P_{max}$ (kW) | 1000 | 1000 | 1000 | 1000 | 1000 | 100 |
| $P_{FC}$ (kW) | 100 | 100 | 100 | 100 | 100 | 100 |
| Annual FC operating hours | 8722 | 8708 | 8725 | 8666 | 8695 | 8695 |
| $M_{stor,max}$ (kg) | 413 | 413 | 413 | 413 | 413 | 41.3 |
| NPV (€) | $1.17\ 10^{5}$ | $1.06\ 10^{5}$ | $4.68\ 10^{4}$ | $2.42\ 10^{4}$ | $3.25\ 10^{4}$ | $-1.72\ 10^{6}$ |
| IRR | $1.00\ 10^{-2}$ | $9.10\ 10^{-3}$ | $4.00\ 10^{-3}$ | $2.10\ 10^{-3}$ | $2.80\ 10^{-3}$ | - |
| Annual total $m_{FC,H2}$ (kg) | $2.62\ 10^{4}$ | $2.61\ 10^{4}$ | $2.62\ 10^{4}$ | $2.60\ 10^{4}$ | $2.61\ 10^{4}$ | $1.50\ 10^{4}$ |
| Annual total $M_{FUEL}$ (kg) | $1.24\ 10^{5}$ | $1.24\ 10^{5}$ | $1.24\ 10^{5}$ | $1.24\ 10^{5}$ | $1.24\ 10^{5}$ | - |
| $Price_{H2}$ (€/kg$H_2$) | 4.4 | 4.0 | 4.2 | 4.4 | 5.1 | - |

Based on the results presented in Table 4.2.8, the sizing algorithm outcome was a selection of the highest and lowest end of the range of the water electrolysis and FC systems, respectively. Taking into consideration the results of SC4.1, it appears that from an investor's perspective, the system should aim for the highest possible hydrogen production to cope with the negative results by fully participating in the electricity markets as producer. In the case of no participation in the transportation market (column '2018 b' in Table 4.2.8), the NPV was lower than the one in SC4.1, where hydrogen is delivered externally. Additionally, the algorithm calculated among the given rated power range of the electrolyser and the FC the lowest values for both components in order to cope with the high capital costs. Annual FC operating hours were slightly lower in this SC due to the negligible time incompatibility of the electrolyser-FC simultaneous operation.

The $Price_{H2}$ is between 4.0 and 5.1 €/kg$H_2$ depending on the revenue from selling the FC-produced electricity to the electricity markets and the electricity costs for producing the hydrogen gas. To this end, one could expect that higher electricity prices would allow for a decrease of the hydrogen fuel costs. This is not confirmed due to the increased operating costs of hydrogen production preventing the decrease of the hydrogen gas price. Quite the contrary, it is proved that the price of hydrogen fuel is negatively affected by higher values. Nevertheless, the price range of the electrolytically produced hydrogen fuel to be sold in the transportation sector is considered at the low end compared to the data given in the international literature (Apostolou and Enevoldsen, 2019), though it is considered higher than conventional ways of producing hydrogen (IEA, 2019c).

#### 4.2.3.2.2. Scenario 4.2b

SC4.2b concerns the operation of the water electrolysis system using excess wind power production only, i.e. excess wind power that had not been used to cover the electricity demand in DK1. In this case, the operating hours of the hydrogen production system are substantially lower than SC4.2a, and hence the hydrogen production is significantly lower. Similar to SC4.2a, a $M_{FUEL}$ equal to zero corresponds to SC4.1 with an electrolysis-storage system inclusion showing an even lower NPV compared to column '2018 b' in Table 4.2.8 and thus it was not further investigated. The results of the applied algorithm are presented in Table 4.2.9.

The results included in Table 4.2.9 show that in SC4.2b, the selling price of the available hydrogen for the transportation market is markedly high and not realistically acceptable. This is because the quantity of hydrogen produced is too limited due to the low operating time of the water electrolysis system, allowing only a small quantity to be sold in the transportation market compared to SC4.2a. Additionally, the revenue from selling electricity to the network along with the capital cost of the investment cannot offset the cost of participating in the electricity markets as consumers (i.e. hydrogen production), and thus the cost of selling hydrogen in the transportation market is calculated to be much higher to cover the annual expenses of the investment compared to SC4.2a.

Table 4.2.9. Optimisation results showing the best cases of integrating a hydrogen system operating during excess wind energy in the electricity and transportation markets.

| **Parameter** | **2014** | **2015** | **2016** | **2017** | **2018** |
|---|---|---|---|---|---|
| $P_{max}$ (kW) | 1000 | 1000 | 1000 | 1000 | 1000 |
| $P_{FC}$ (kW) | 100 | 100 | 100 | 100 | 100 |
| Annual electr. operating hours | 1231 | 1442 | 1167 | 1510 | 1248 |
| Annual FC operating hours | 5733 | 6773 | 5561 | 6878 | 6201 |
| $M_{stor,max}$ (kg) | 412 | 412 | 412 | 412 | 412 |
| NPV (€) | $3.18\ 10^{4}$ | $5.28\ 10^{4}$ | $5.88\ 10^{4}$ | $4.22\ 10^{4}$ | $5.44\ 10^{4}$ |
| IRR | $2.70\ 10^{-3}$ | $4.50\ 10^{-3}$ | $5.00\ 10^{-3}$ | $3.60\ 10^{-3}$ | $4.70\ 10^{-3}$ |
| Excess wind energy (MWh) | $5.48\ 10^{5}$ | $6.34\ 10^{5}$ | $5.66\ 10^{5}$ | $7.42\ 10^{5}$ | $5.97\ 10^{5}$ |
| Annual total $m_{FC,H2}$ (kg) | $1.72\ 10^{4}$ | $2.03\ 10^{4}$ | $1.66\ 10^{4}$ | $2.06\ 10^{4}$ | $1.86\ 10^{4}$ |
| Annual total $M_{FUEL}$ (kg) | $3.95\ 10^{3}$ | $4.45\ 10^{3}$ | $3.37\ 10^{3}$ | $5.11\ 10^{3}$ | $2.83\ 10^{3}$ |
| $Price_{H2}$ (€/kg$H_2$) | 81 | 71 | 94 | 60 | 114 |

By comparing the years 2014 and 2016, one may notice that although the excess wind energy in 2016 was higher than in 2014, the annual electrolysis operating hours and thus the hydrogen production were lower. This is because the amount of excess wind energy in 2016 was higher than in 2014, while the annual hours of excess wind power were lower. Hence, although the amount of annual excess wind energy plays a positive role for hydrogen production and, consequently, for hydrogen fuel costs, the operating hours of the system and the amount of available energy that can be absorbed by the electrolyser seem to be more significant.

It is also apparent that as hydrogen production increases, the price of hydrogen to be sold in the transportation sector decreases, indicating that with an increase in excess wind power in the future due to an increase in the number of new wind power installations, the more appealing such investments that take advantage of the non-integrated wind energy will be.

The author also examined the operation of the water electrolysis system during periods of excess wind power generation and only under negative electricity prices to eliminate the electricity cost of the hydrogen production process. The examined case resulted in very low hydrogen production, which cannot generate revenue from the participation of the FC system in the electricity markets and from the remaining hydrogen fuel in the transportation sector to overcome investment cost.

### 4.2.3.3 Investigated scenario 4.3

The third scenario consists of two cases similar to SC4.2, including a) continuous operation of a water electrolysis system to provide hydrogen as transportation fuel (i.e. SC4.3a) and b) operation only during periods of excess wind power production (i.e. SC4.3b).

#### 4.2.3.3.1. Scenario 4.3a

The continuous operation of the water electrolysis system allows large production of hydrogen depending on the rated power of the electrolyser, though the developed model calculates the best solution for having an economically viable business, while at the same time keeping the selling price of hydrogen fuel as low as possible. The results of the algorithm application are shown in Table 4.2.10.

Table 4.2.10. Optimisation results showing the best cases of integrating a hydrogen production-storage system with continuous operation in the transportation market.

| Parameter | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|
| $P_{max}$ (kW) | 400 | 420 | 440 | 440 | 440 |
| Annual cost of electricity (€) | $1.02\ 10^5$ | $8.42\ 10^4$ | $1.03\ 10^5$ | $1.16\ 10^5$ | $1.70\ 10^5$ |
| $M_{stor,max}$ (kg) | 165.2 | 173.5 | 181.7 | 181.7 | 181.7 |
| NPV (€) | $3.60\ 10^3$ | $4.43\ 10^3$ | $1.96\ 10^4$ | $1.54\ 10^4$ | $5.18\ 10^3$ |
| IRR | $8.25\ 10^{-4}$ | $9.75\ 10^{-4}$ | $4.10\ 10^{-3}$ | $3.30\ 10^{-3}$ | $1.10\ 10^{-3}$ |
| Annual total $M_{FUEL}$ (kg) | $6.01\ 10^4$ | $6.32\ 10^4$ | $6.64\ 10^4$ | $6.62\ 10^4$ | $6.62\ 10^4$ |
| $Price_{H2}$ (€/kg$H_2$) | 4.0 | 3.6 | 3.8 | 4.0 | 4.8 |

Based on the model outcome presented in Table 4.2.10, the positive investment factors of NPV and IRR are found for the electrolyser's rated power between 400 and 440 kW, while the lowest $Price_{H2}$ ranges from 3.6 to 4.8 €/kg$H_2$. By comparing the last cases for the years 2016-2018, it can be found that the increasing price of hydrogen fuel stems from the increasing electricity costs during participation in the hydrogen production unit as a consumer in the electricity markets. Additionally, the hydrogen production costs are lower compared to those of SC4.2a due to the mid-scale electrolyser unit and the absence of the FC system. The range of the hydrogen fuel price is similar to the low end of hydrogen cost values from the water electrolysis, but higher than the cost of hydrogen produced from fossil fuels (IEA, 2019c).

#### 4.2.3.3.2. Scenario 4.3b

The operation of the water electrolysis system during periods of excess wind power resulted in lower production of hydrogen fuel, and together with the main capital expenditure components, the selling price of hydrogen to have a profitable business case was calculated to be higher than SC4.3a. The results of the algorithm for SC4.3b are presented in Table 4.2.11.

Table 4.2.11. Optimisation results showing the best cases of integrating a hydrogen production-storage system during excess wind energy in the transportation market.

| Parameter | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|
| $P_{max}$ (kW) | 1000 | 1000 | 1000 | 950 | 1000 |
| Annual cost of electricity (€) | 2.88 $10^4$ | 2.06 $10^4$ | 2.15 $10^4$ | 2.74 $10^4$ | 3.86 $10^4$ |
| $M_{stor,max}$ (kg) | 412 | 412 | 412 | 391 | 412 |
| NPV (€) | 5.26 $10^3$ | 1.89 $10^4$ | 1.92 $10^4$ | 0.57 $10^3$ | 1.20 $10^4$ |
| IRR | 0.53 $10^{-3}$ | 1.90 $10^{-3}$ | 2.00 $10^{-3}$ | 6.08 $10^{-5}$ | 1.20 $10^{-3}$ |
| Excess wind energy (MWh) | 5.48 $10^5$ | 6.34 $10^5$ | 5.66 $10^5$ | 7.42 $10^5$ | 5.97 $10^5$ |
| Annual total $M_{FUEL}$ (kg) | 2.11 $10^4$ | 2.47 $10^4$ | 2.00 $10^4$ | 2.46 $10^4$ | 2.14 $10^4$ |
| $Price_{H2}$ (€/kg$H_2$) | 14.5 | 12.1 | 15.0 | 11.9 | 14.8 |

The results derived for SC4.3b showed that to have the lowest hydrogen selling price in the years investigated, an investment at the high-end range (i.e. 950 and 1000 kW) of the electrolyser's rated power is required. The $Price_{H2}$ is between 11.9 and 15.0 €/kg$H_2$ and depends mainly on the annual production of the fuel together with the electricity prices (see 'Annual cost of electricity' in Table 4.2.11). For example, although in 2016 and 2018, the rated power of the electrolysis system was the same and the annual cost of electricity in 2018 was higher than in 2016, the $Price_{H2}$ is calculated to be lower due to the higher hydrogen production as a result of more frequent operation of the system. In addition, the annual excess wind energy seems to play a major role in the price of the hydrogen fuel, with greater availability of excess wind energy favouring the price of the fuel. However, it is apparent that, as in SC4.2b, this must be aligned with the frequency of excess wind energy throughout the year. So in 2014, the total wind energy was lower than in 2016, but it was distributed over several hours, allowing the electrolysis system to operate more frequently and produce larger amounts of hydrogen fuel.

#### 4.2.3.4 Main outcome

The development and application of the sizing algorithm for a hydrogen system integrated into the electricity and transportation markets have provided the specifications of the system and the hydrogen selling price to have a viable business SC. The novelty of this paper lies in two main aspects:

1. The algorithm is able to interact with the specifications of the system and the respective inputs of the under investigation electricity markets, and
2. The developed methodology, which is the keystone of a viable, multi-purpose hydrogen system in the energy and transportation sectors, can be used to identify how costs and prices (electricity and hydrogen fuel) must change towards an economically sustainable hydrogen market.

The application of the developed algorithm for finding the optimal business case scenario revealed that, currently, a hydrogen production-storage and repowering system participating in the Danish electricity market is not economically viable. Both investment and O&M costs need to be unrealistically reduced (by at least 70% and 90%, respectively), or electricity market prices should increase to meet the high capital and O&M costs of hydrogen technologies. However, this outcome only applies to the specific case study on the status of the Danish electricity system. The developed algorithm can also be implemented in other countries or autonomous electrical systems, where other results may be obtained. As for the investigated case study, it seems that the introduction of hydrogen technologies for energy storage in the electrical grid is not currently an economically viable solution. With increased RES capacity and consequently excess energy, along with a significant decrease in the capital and O&M costs associated with hydrogen technologies, such investments could become more feasible.

On the other hand, the results showed that an investor could profit from the participation of a hydrogen configuration in both the electricity and/or transportation markets depending on the selling price of the hydrogen fuel for transportation.

Acknowledging the above analysed SCs, the most realistic results have been derived in SC4.2a and SC4.3a, while the hydrogen price results for SC4.3b can be considered within the range given in peer-reviewed literature (Apostolou and Enevoldsen, 2019). Fig. 4.2.8 presents the hydrogen price range of these SCs along with the hydrogen cost given in other indicative studies.

SC4.2a and SC4.2b present the hydrogen price values lower than the average depicted in most of the other recent studies in Fig. 4.2.8. This is because most of these studies include, in their estimations, a RES generator to operate the water electrolysis system. To this end, the hydrogen fuel costs are increased by 2 to 16 €/kg$H_2$ depending on the case investigated.

Even though the hydrogen fuel selling price of the above-mentioned SCs is considered low compared to the other studies in Fig. 4.2.8, it is still approximately double than the highest price of hydrogen produced from NG (i.e. 2.1 €/kg$H_2$ (IEA, 2019c)). Hence, although fossil fuel-based production of hydrogen is carbon-intensive, it currently provides a more appealing choice for the end-users of hydrogen in the transportation sector. However, a reduction in the investment and O&M costs or/and a financial support from state authorities may contribute to a decrease in the selling price of hydrogen fuel produced from emission-free water electrolysis to competitive values.

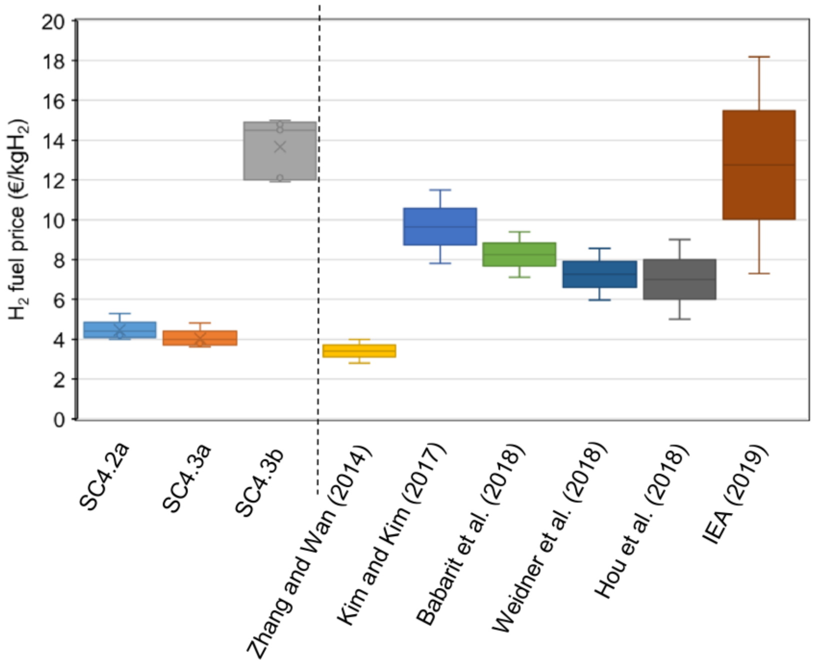



Fig. 4.2.8. Range of wholesale hydrogen price results based on the examined SCs and respective values found in literature. Based on (Babarit et al., 2018; Hou et al., 2017; IEA, 2019c; Kim and Kim, 2017; Weidner et al., 2018; Zhang and Wan, 2014).

### 4.2.4 Conclusions

The aim of this research was to provide a tool for assessing the prospects of integrating a hydrogen system into the electricity and/or transportation markets to sustainably support their growth towards a zero-carbon emission future. To this end, an algorithm was developed to interact with inputs from the electricity market prices, the electricity surplus/deficit and the excess wind power in the grid to evaluate the investment financially. In addition, the developed model simulated the processes occurring during the hydrogen production, storage and repowering stages for calculating the optimal size of the system to ensure the lowest possible wholesale price of hydrogen fuel for transportation, while at the same time providing grid support when required.

The investigation of the three scenarios regarding the participation of the hydrogen system in the Danish electricity and/or transportation markets showed that participation in both markets could be economically feasible, but limitations of the system's operating hours could contribute to increased hydrogen fuel prices. Although scenario 1 currently does not seem viable in terms of business prospects, a significant reduction in the capital costs could alter the outcome in favour of this topology. Scenarios 4.2a and 4.3a, on the other hand, present the highest prospects from a business perspective, indicating that continuous operation of the hydrogen production unit and thus higher hydrogen production would allow for more cost-competitive prices compared to conventional fuels in the transportation sector.

In conclusion, the integration of ‘green’ hydrogen technologies in the Danish electricity market and the use of the produced hydrogen as a bi-product (i.e. for repowering applications and as a fuel for transportation) show positive prospects from a business case perspective. The Danish electricity system allows high penetration of renewable energy due to the interconnections with the neighbouring countries and does not currently require the use of large-scale energy storage topologies. However, as the renewable energy capacity increases, energy storage configurations will be essential for managing energy waste. In contrast to the investigated case study, electricity networks in other countries present still less flexibility in terms of renewable energy integration. To this end, the developed algorithm and the methodology followed can easily be applied to identify the best scenarios for implementing hydrogen technologies in the respective electricity and/or transportation markets, allowing an increased penetration of renewable energy sources. Hence, the adoption of such a solution documented by the analysed SCs could be deemed to depend on two main factors. First, on the reduction of the systems’ capital costs and second on the emerging necessity to implement these topologies to facilitate the expansion of multiple markets such as the ones of transportation and electricity. One may also argue that the conditions to make these SCs commercially realistic also include the level of maturity of those systems in the energy markets. The implementation of technologies that are not widely tested in medium-to-large scale applications could become an obstacle toward the propensity of investors to invest in such systems and therefore their commercialised expansion could be hindered.

Although there are still drawbacks in terms of higher costs compared to other competitive technologies in the repowering sector, such as pumped-hydro storage, the versatile characteristics of the hydrogen product make it ideal to use for various applications (e.g. transportation, industry, power sector and heating purposes), positively countering the negatives arising from using it in one sector only.

# 5. Which type of hydrogen refuelling infrastructure for cycling-based transportation is the most economically feasible solution from an investor and customer perspective?

The main objective of the third RQ was to assess the different types of HRSs suitable for light-duty urban vehicles such as FCEBs or FCESs in order to identify the best financially appealing SC from the perspective of both hydrogen technologies stakeholders and future consumers. The examination and in-depth analysis of the prospects of each HRS type have been aligned to the research scope of the following four journal articles:

- D. Apostolou, P. Enevoldsen, G. Xydis (2019). Supporting green urban mobility – The case of a small scale autonomous $H_2$ refuelling station. *International Journal of Hydrogen Energy*, 44(20), pp. 9675-9689, https://doi.org/10.1016/j.ijhydene.2018.11.197.

- D. Apostolou (2020). Assessing the operation and different refuelling cost scenarios of a fuel cell electric bicycle under low-pressure hydrogen storage. *International Journal of Hydrogen Energy*, 45(43), pp. 23587-23602, https://doi.org/10.1016/j.ijhydene.2020.06.071.

- D. Apostolou, P. Casero, V. Gil, G. Xydis (2021). Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market. *International Journal of Hydrogen Energy*, 46(7), pp. 5756-5762. https://doi.org/10.1016/j.ijhydene.2020.11.047

- D. Apostolou (2021). Refuelling scenarios of a light urban fuel cell vehicle with metal hydride hydrogen storage. Comparison with compressed hydrogen storage counterpart. *Energy Transitions*. Under review.

## 5.1 Supporting green urban mobility – The case of a small scale autonomous $H_2$ refuelling station

Nowadays, the development of hydrogen economy in the transportation sector is hindered by the principal barriers arising from the lack of adequate infrastructure and the small fleet of hydrogen-based road vehicles.

This study investigates the potential of small-scale autonomous hydrogen refuelling stations with on-site production via an alkaline electrolysis apparatus powered by a small wind turbine. In this context, an urban area with promising wind resources has been selected. Based on the wind conditions and an indicative hydrogen demand for refuelling light-duty fuel cell electric vehicles such as bicycles, the sizing of the wind turbine and the electrolyser has been theoretically calculated. For supporting the daily hydrogen refuelling demand of the fuel cell electric bicycles, which is estimated at approximately 6 kg, it is calculated that a 50 kW wind turbine should be installed in order to power a 70 kW alkaline electrolyser for producing hydrogen. The capital cost of the hydrogen station is calculated at €248,130, while the retail price of the produced hydrogen is estimated to be more than 50.2 €/kg$H_2$ in order to achieve a positive internal rate of return.

Ultimately, the present paper aims at delivering a feasibility study of a small-scale $H_2$ refuelling station for fuel cell bicycles in order to provide investors with initiatives to implement such schemes in urban environments where problems of low air quality and high traffic are intense.

### 5.1.1 Introduction

Today, although the transition to environmentally friendlier means of transportation faces several challenges, green mobility develops continuously, owing to the introduction of new vehicle concepts and refuelling technologies based on RES (Bekiaris et al., 2017; Morrison et al., 2018). One of the most promising options for supporting green transportation is the use of hydrogen as a fuel. A comparative study performed by Bicer and Dincer in 2017 indicated that hydrogen-based vehicles present more environmental benefits in a life cycle assessment as compared to electric and methanol vehicles. Specifically, the authors concluded that the global warming potential of hydrogen vehicles is approximately three times lower than the other investigated green vehicles (Bicer and Dincer, 2017).

Since Toyota introduced the first commercialised FCEV in 2015, many other automotive industries followed suit, deploying FCEV models in order to keep up with the emerging hydrogen market in the transportation sector.

However, this trend moving towards hydrogen mobility seems to be hindered by several factors such as lack of adequate infrastructure and high cost of ownership (Brey et al., 2018; Michalski et al., 2011). As for hydrogen infrastructure and specifically HRSs, more than 315 stations are in operation today with at least 2/3 of them representing publicly accessible refuelling spots (Ludwig-Bölkow-Systemtechnik, 2017; SÜD, 2017; Wasserstoff-Tankstellen weltweit, 2017). The region with the most HRSs in operation at the beginning of 2018 was Europe with more than 130 HRSs, while Asia ranked second with approximately 120 HRSs, mostly located in Japan. America came in third with more than 60 stations installed (mostly in USA) (SÜD, 2017). Fig. 5.1.1 illustrates how operative HRSs are distributed globally, highlighting the regions where the new hydrogen market emerges. However, the main barriers that limit the rapid deployment of new hydrogen infrastructure stem from the low number of on-road FCEVs and the high capital investment of an HRS.


Fig. 5.1.1. HRSs in operation, early 2018. Adapted from (Wasserstoff-Tankstellen weltweit, 2017).

At this time, the number of FCEVs reaches 6,000, with more than 2,500 units sold in 2017. Although Europe, compared to other regions, has a more developed hydrogen network in terms of HRSs (see Fig. 5.1.1), the leader in FCEVs is North America with more than 50% of total vehicles, followed by Asia with 40% and, lastly, Europe with a 10% share of the FCEV fleet (Information Trends, 2018). On the other hand, the capital cost of an HRS can still be considered prohibitive for small investors, and depending on the capacity (kg/day of $H_2$), the type of the station (On-site Steam Methane Reformer or Electrolysis, Delivered Gaseous $H_2$ or Liquid $H_2$) and the country where the HRS is installed, it ranges between \$0.85 million and \$4.5 million (Mayyas, 2015; Mayyas and Mann, 2016).

Although hydrogen fuel can be produced via several methods, the most appealing in terms of environmental benefits is through water electrolysis powered by RES. One of the most mature renewable technologies comprises wind power, and many researches analyse the coupling of wind power with water electrolysis topologies. Greiner et al. (2007) presented a sizing and optimisation method for a hydrogen system powered by wind energy in a Norwegian island based on the demand of a hypothetical $H_2$-propelled vessel (Greiner et al., 2007). A techno-economic analysis of wind power produced hydrogen was published by Gökçek (2010). The author concluded that the operation of the system presented high variations of hydrogen production based on the available wind resource, and the levelised cost of hydrogen ranged between 12.5 €/kg$H_2$ and 18.9 €/kg$H_2$ (Gökçek, 2010). Likewise, Genç et al. (2012) financially analysed a wind power hydrogen system, presenting results for hydrogen fuel cost between 7.3 €/kg$H_2$ and 26.6 €/kg$H_2$ based on different wind and water electrolysis topologies (Genç et al., 2012). On the other hand, Ulleberg et al. (2010) analysed the results of a pilot wind power electrolysis system in Norway, and argued that for having an efficient system it is required to install efficient electrolysers able to operate dynamically (Ulleberg et al., 2010). More recently (Kim and Kim, 2017) compared wind onshore and offshore installations coupled with a centralised water electrolysis unit and indicated a levelised $H_2$ cost between 8.93 €/kg$H_2$ and 13.1 €/kg$H_2$. Hou et al (2017) on the other hand, presented business cases on wind energy-based hydrogen production where it is demonstrated that a cost of hydrogen for power to gas applications should be above 5 €/kg$H_2$ in order to have an economically viable scenario (Hou et al., 2017).

Hydrogen as a renewable energy storage medium presents today an appealing technology to many applications. During the last decade, the scientific community studied the utilisation of hydrogen for mobility purposes through the research on FCEVs and $H_2$ refuelling processes. Ahmadi and Kjeang (2015) examined the prospects of FCEVs in Canada through a life cycle assessment based on different technologies used for the production of hydrogen fuel. Specifically, $H_2$ production through thermochemical process by using renewable waste heat presented the best life cycle cost compared to other $H_2$ and gasoline technologies (Ahmadi and Kjeang, 2015). Reddi et al. (2017) presented a techno-economic evaluation regarding HRSs, pointing out that current dispenser prices of $H_2$ fuel in USA ranges between 11.4 €/kg$H_2$ and 13.2 €/kg$H_2$ and are highly dependent on the technologies used and the capacity of the station (Reddi et al., 2017). A cost analysis of hydrogen fuel based on two scenarios of FCEV deployment in Normandy has been published by (Brunet and Ponssard, 2017). The outcomes of the research indicated that moving to higher capacity of HRSs to cover an increased fleet of FCEVs, will result to an $H_2$ production cost of approximately 5 €/kg$H_2$. Ezzat and Dincer (2018) presented their research on a hydrogen-ammonia system for FCEVs able to recover hydrogen during the operation of the vehicle through an ammonia electrolyte electrolyser powered from on-board photovoltaics. The results indicated that the system can produce and store approximately 314 g$H_2$ during 1 hour of operation of the vehicle under an output power of 98.3 kW (Ezzat and Dincer, 2018).

Apart from the commercialisation of medium-scale passenger FCEVs, many studies conducted since 2000 focused in developing light-duty fuel cell vehicles such as scooters and bicycles at a relatively low cost of ownership. In 2002, Cardinali et al. tested a modified electric bicycle charged by a fuel cell and published their results on the system's efficiency and the components' performance (Cardinali et al., 2002). Tso and Chang (2003) revealed the necessity of integrating fuel cell scooters in Taiwan and presented the promotional activities initiated by the local government (Tso and Chang, 2003). A hydrogen bicycle's development and performance in correlation with its efficiency and autonomy have been investigated by Hwang et al. (2004) who concluded that this technology under commercialisation would be profitable (Hwang et al., 2004). In 2005, Hwang et al. also described the development of a light-duty fuel cell vehicle and reported positive results in terms of performance and efficiency of the vehicle compared to conventional ones (Hwang et al., 2005). Indicative research on specifications and cost analysis of a hydrogen scooter has been presented by Chao et al. (2009) through the modelling of a Taiwan fuel cell scooter. The authors evaluated the performance of the scooter based on their simulation results and suggested that the cost of ownership is directly comparable with that of a conventional scooter (Chao et al., 2009). Tso et al. (2012) analysed the results of a project where 30 fuel cell scooters were tested under various conditions and across different route patterns and driving profiles. The results showed adequate technical feasibility of the scooters, but also revealed parameters such as driving performance, hydrogen storage and outdoor temperature in correlation to hydrogen storage that need to be considered when developing this kind of vehicle (Tso et al., 2012). Tolj et al. (2013) studied the performance of a fuel cell used as a range extender of an electric golf cart. The authors demonstrated a range extension of 63% and up to 110% (Tolj et al., 2013). Another research conducted by Kheirandish et al. (2014) was based on experimental investigation of a fuel cell bicycle. Their results showed that hydrogen-based vehicles are superior to conventional vehicles operating in urban environments (Kheirandish et al., 2014).

Taking the above into consideration, it is obvious that a new market of hydrogen-powered light vehicles is emerging. Hence, in order to support the growth of this urban hydrogen mobility, it is imperative to promote feasible solutions concerning the refuelling processes. To this end, this paper analyses the potential of a small HRS for cycling transportation with on-site hydrogen production via electrolysis powered by a small WT installed near urban areas. The main purpose of this research is to present a low-cost solution for small HRSs providing $H_2$ to light-duty vehicles such as FCEBs, primarily in countries where this mean of transportation dominates in urban regions.

### 5.1.2 Methodology

The proposed methodology consists of four main sections, where a detailed analysis of the proposed configuration is described in both technical and financial terms. Fig. 5.1.2 presents a schematic outline of the system under study, consisting of a small wind turbine, an alkaline electrolyser, auxiliary systems, a hydrogen buffer tank and a low-pressure output $H_2$ compressor for keeping the refuelling pressure constant. Fig. 5.1.3 indicates the steps followed during the review of the technical aspects of this topic, including the sizing of the wind turbine based on the available wind resource and an assumed average number of FCEBs to be daily refuelled, the sizing and optimisation of an alkaline electrolyser able to absorb the highest amount of the produced wind-based electricity. The sizing of the low-pressure $H_2$ buffer tank and the exact number of FCEBs that can be refuelled on a daily basis have been determined subsequently. Auxiliary components such as the $H_2$ compressor are assumed to be electrically supplied directly from the grid.

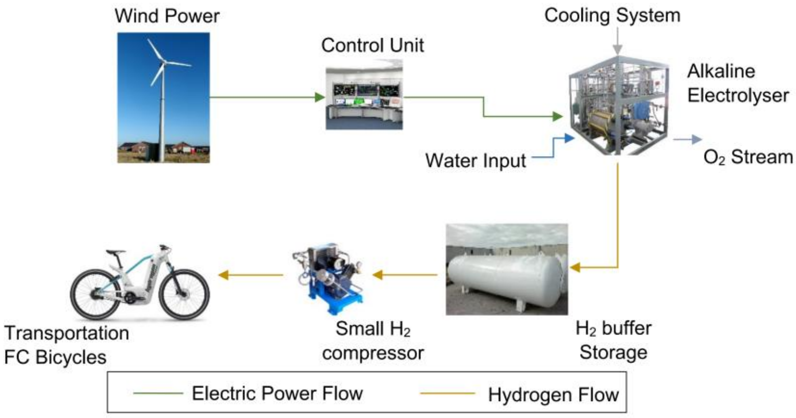



Fig. 5.1.2. Proposed small HRS configuration.

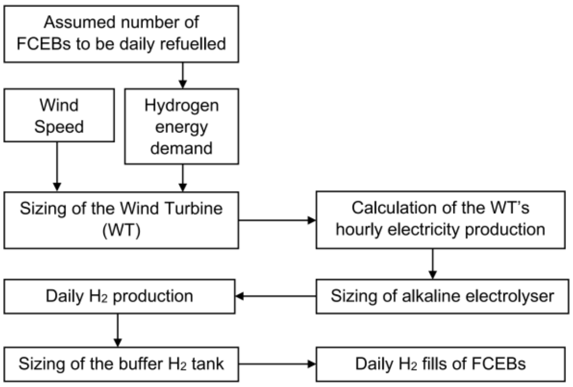



Fig. 5.1.3. Main steps of the sizing process.

Following the above, the last part of this paper's methodology section presents a financial evaluation of the proposed topology in order to provide future stakeholders and investors with all the necessary data and results on a hydrogen economy in the transportation sector.

### 5.1.2.1 Sizing of the wind turbine

As it was previously mentioned, the first step in the investigation of a small HRS near an urban environment consists in the sizing of the wind turbine on the basis of an estimate of the final energy needed to daily refuel a certain number of FCEBs and the available wind speed data on the specific region to be studied.

The urban environment under investigation is the city of Herning, which is located in central Jutland in Denmark. The city's population in 2017 was 49,229 inhabitants ($N_{inh}$) based on Statistics Denmark (Statistics Denmark, 2018a), while the percentage of inhabitants using bicycles on a daily basis is 28%

and the average daily distance covered ($D_{dist}$) approximates 1.5 km/cyclist (Cycling Embassy of Denmark, 2015).

The region's average annual wind speed at 25 m above ground level is approximately 6 m/s. The area of the wind measurements and the proposed location of the WT and the HRS are indicated in Fig. 5.1.4.

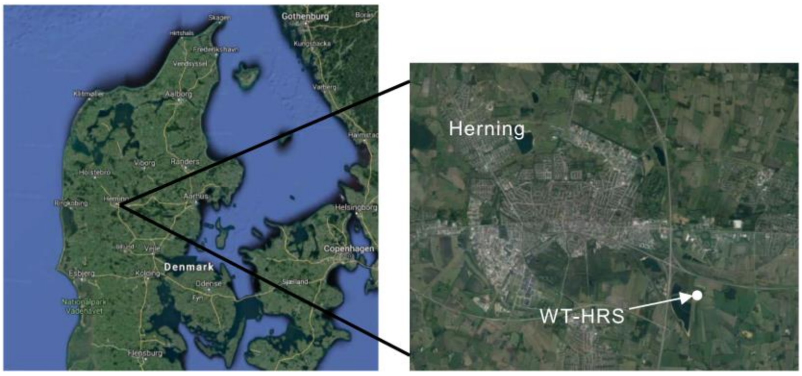



Fig. 5.1.4. Location of the wind turbine and hydrogen refuelling station.

The specifications of the FCEB are presented in Table 5.1.1. According to the data given, the FCEB has an autonomy of 100 km with a maximum quantity of 30 g$H_2$ stored in its fuel tank at a pressure of 200 bar and a fully charged battery. However, based on Boyle's law (see Eq. 5.1.1) and the specific density of hydrogen, one can obtain the quantity of the hydrogen stored in g ($m_{H,stored}$) under lower pressure (i.e. 30 bar) assuming constant temperature (Webster, 1963).

$$p_1 v_1 = p_2 v_2 \tag{5.1.1}$$

Table 5.1.1. Specifications of the FCEB (Pragma Industries, 2017).

| Parameter | Value | Units |
|---|---|---|
| Motor power | 250 | W |
| Motor voltage | 36 | V |
| Fuel cell rated power | 150 | W |
| Water volume of the $H_2$ tank | 2 | L |
| Maximum $H_2$ storage pressure | 200 | bar |
| Quantity of $H_2$ at maximum pressure | 30 | g |
| Max. riding range at maximum $H_2$ storage | 100 | km |
| Average time for refill | 2 | min |

In this regard, the daily number of refuelled bicycles can be estimated by dividing the number of bicycles used daily (28% of Herning's population) with the average days of each bicycle's autonomy ($R_{bike}/D_{dist}$) (see Eq. 5.1.2).

$$N_{bikes} = N_{inh} \quad 0.28 \quad / \left(\frac{R_{bike}}{D_{dist}}\right) \tag{5.1.2}$$

where $N_{bikes}$ is the estimated total number of refuelled FCEBs per day, and $R_{bike}$ is the average range of the FCEB refuelled at 30 bar of $H_2$ pressure.

However, on account of the magnitude of refills that may result from Eq. 5.1.2, one refuelling hose may not be able to cover the demand due to the specific time required to refill one FCEB. To this end, based on the time to refill ($t_{refill}$) a FCEB (taking also into account the time used on other procedures in the process such as. the purchase procedure) equalling, the maximum number of FCEBs/refuelling hose served daily from one HRS ($N_{bikes,hose}$) can be calculated via Eq. 5.1.3, where $h_{day}$ represents the daily hours.

$$N_{bikes,hose} = \frac{h_{day}\ \ 60}{t_{refill}} \tag{5.1.3}$$

In addition, the total number of HRS hoses ($N_{HRS,hoses}$) can be estimated through Eq. 5.1.4.

$$N_{HRS,hoses} = \frac{N_{bikes}}{N_{bikes,hoses}} \tag{5.1.4}$$

Acknowledging the above and the electricity demand of an electrolyser ($E_{el}$) (Apostolou, 2015), Eq. 5.1.5 calculates the average annual electricity production of the wind turbine ($E_{WT}$) (kWh) required to cover the hydrogen demand of the FCEBs.

$$E_{WT} = N_{bikes}\ \ E_{el}\ \ N_{days} = \ \ N_{bikes}\ \ \left(\frac{m_{H,stored}\ \ LHV_{H2}}{\eta_{el}}\right)\ \ N_{days} \tag{5.1.5}$$

$LHV_{H2}$ is the low heating value of hydrogen in kWh/g, $\eta_{el}$ is the electrolyser's efficiency which is assumed to be 60% (LHV-based) (IEA, 2015) and $N_{days}$ represents the days of the year.

The WT's rated power ($P_R$) can then be calculated by taking into account the capacity factor (CF) of its annual operation (hours of the year, $h_{year}$) through Eq. 5.1.6 (Kaldellis and Apostolou, 2017). The CF can be designated via Eq. 5.1.7, where $\Delta$ represents the technical availability of the WT, indicating the ability of a wind turbine to operate with minimal downtime and thus produce higher energy yield. The technical availability of small wind turbines is lower than larger converters and may reach approximately 91% (Bowen et al., 2009). On the other hand, $\omega$ is the mean power coefficient, which is dependent on the wind resource and can be calculated via Eq. 5.1.8 (Kaldellis and Apostolou, 2017).

$$E_{WT} = CF\ \ P_R\ \ h_{year} \tag{5.1.6}$$

$$CF = \omega\ \ \Delta \tag{5.1.7}$$

$$\omega = \int_0^{\infty} \frac{P_{ex}(V)}{P_R} f(V)dV = \int_{V_c}^{V_f} \frac{P_{ex}(V)}{P_R} f(V)dV \tag{5.1.8}$$

$f(V)$ represents the probability density curve of the wind speed, $V$, and can be calculated through the Weibull distribution (see Eq. 5.1.9) (Akdağ and Dinler, 2009), $P_{ex}(V)/P_R$ corresponds to the non-dimensional power curve (see Fig. 5.1.5) of the wind turbine with $P_{ex}(V)$ being the power output of the wind converter (of $P_R$-rated power) at different wind speeds, $V$, at hub height. $V_c$ and $V_f$ are the cut-in and cut-out speed of the wind turbine, respectively (Kaldellis and Apostolou, 2017).

$$f(V) = \frac{k}{c_w} \left(\frac{V}{c_w}\right)^{k-1} e^{-\left(\frac{V}{c_w}\right)^k} \tag{5.1.9}$$

$k$ is the dimensionless shape parameter, and $c_w$ is the scale parameter in units of wind speed. For the calculation of the parameters $k$ and $c$, the authors used the 'Moment Method' proposed in international literature (Akdağ and Dinler, 2009; Usta, 2016), where the local annual wind resource of the region has been used as input (see Fig. 5.1.6).

In this context, it is possible to select a commercial WT able to provide the necessary energy in order to cover the annual hydrogen demand of the FCEBs.

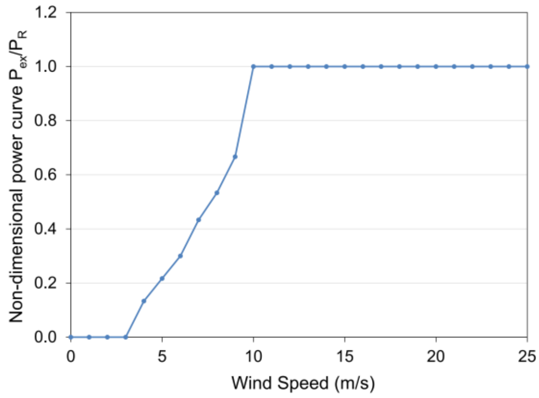



Fig. 5.1.5. Non-Dimensional power curve of a small WT. Based on (HUMMER Industries, 2018).

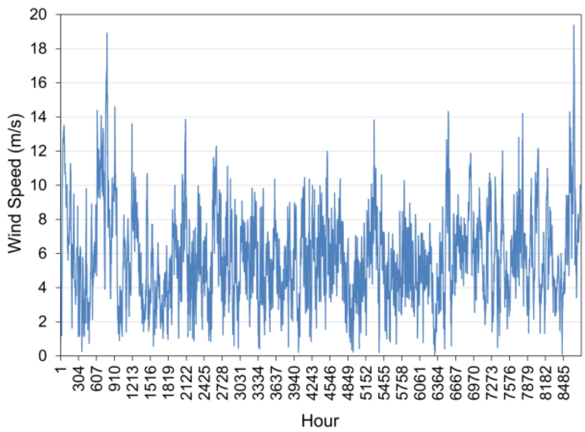



Fig. 5.1.6. 2016 annual wind speed at 25 m height at the proposed location.

### 5.1.2.2 Sizing of the alkaline electrolyser

Considering the power curve of the selected WT given by the manufacturer, the actual annual generated power of the WT can be calculated by using the available wind speed resource (Fig. 5.1.6).

Based on an electrolysis sizing and optimisation algorithm developed by the first author in *MATLAB* code (see Fig. 5.1.7) and by using as input, $P_{in}$, the output power of the wind turbine, the electrolyser's maximum operational power for producing the maximum hydrogen quantity can be calculated (Kavadias et al., 2018).

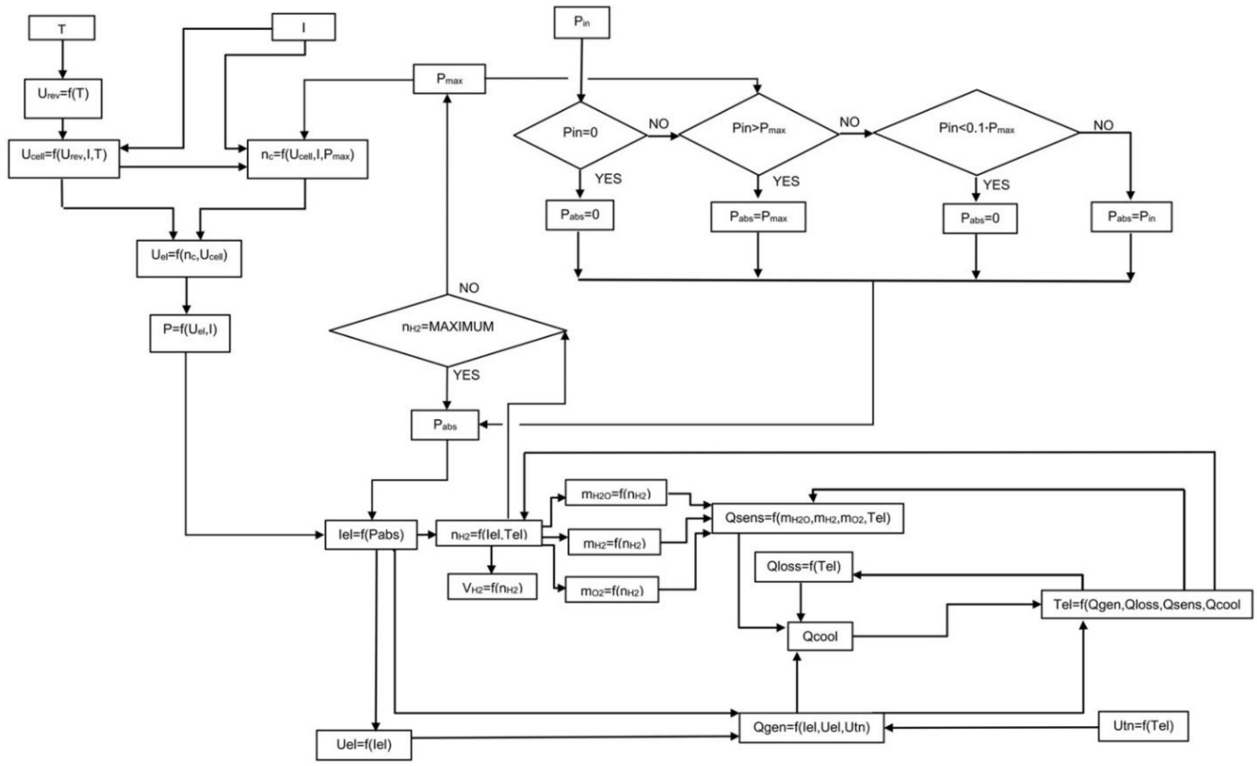



Fig. 5.1.7. Sizing and optimisation algorithm of the alkaline electrolyser. Based on (Apostolou, 2015; Kavadias et al., 2018).

In Fig. 5.1.7, the upper right section concerns the power absorbed by the electrolyser for different values of rated power ($P_{max}$) depending on the electrolyser's operational power range (e.g. 10% to 100%) and the respective available input. The upper left part of the block diagram displays the estimation of the current-power equations at different operational temperatures, between 10$^{o}$C and 80$^{o}$C, for different values of current ranging from 0 A to 720 A. The electrolysis simulation is presented at the lower part of the figure. In this connection, the algorithm estimates in a loop mode the appropriate size of the electrolyser for producing the maximum hydrogen quantity ($n_{H2}$), and at the same time, it calculates all the parameters associated with the electrolysis process (Kavadias et al., 2018).

The algorithm used to determine the optimum size of the electrolyser, and therefore the electrolysis' additional parameters (e.g. hydrogen production, efficiency), was based on a set of equations (Eq. 4.2.1 to 4.2.5) describing the electrolysis process as well as a heat transfer model proposed by (Diéguez et al., 2008; Kavadias et al., 2018). Through these equations, the voltage current curves of each cell are determined (see Fig. 5.1.8). The specifications of each cell appear from Table 4.2.1.

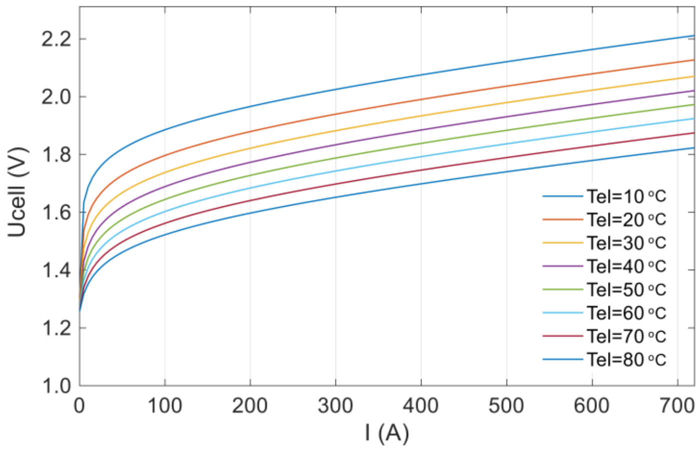



Fig. 5.1.8. Voltage-current curves of the electrolytic cell.

### 5.1.2.3 Sizing of the low-pressure buffer tank – determination of the daily FCEBs refuelling processes

The sizing of the low-pressure buffer tank was based on the daily demand for hydrogen, $M_{H2dem}$. The maximum storage capacity of the tank ($M_{H2bfr}$) is defined in Eq. 5.1.10. However, if the maximum hydrogen production from the electrolyser is higher than the daily $H_2$ demand, then the buffer storage should be able to accommodate this maximum produced quantity.

Thereafter, the buffer tank's water volume ($v_{bfr,WV}$) can be calculated through the maximum value of daily produced hydrogen mass, the specific density of hydrogen and Boyle's law (see Eq. 5.1.1), where $p_1$ and $v_1$ are the pressure and volume of hydrogen at STP conditions, while $p_2$ and $v_2$ are the pressure and volume of hydrogen at 30 bar. $v_2$ equals the water volume of the buffer tank, representing the actual size of the buffer tank for the respective daily storage of the produced hydrogen under pressure of 30 bar.

$$M_{H2bfr} = N_{bikes} \;\; m_{H,stored} \tag{5.1.10}$$

The actual daily number of FCEB ($N_{FCEB}$) refills from the proposed HRS can be determined from the hydrogen mass in the buffer tank ($m_{H2bfr}$), the $H_2$ quantity stored in each FCEB tank ($m_{H,stored}$) and the daily $H_2$ production from the electrolyser ($m_{H2,electr}$). Fig. 5.1.9 indicates the algorithm used for calculating the daily FCEB refuelling processes. In order to secure fuel availability on a daily basis, it is assumed that whenever the hydrogen quantity inside the buffer tank is lower than the daily $H_2$ demand, only half of this quantity can be used for refuelling purposes.

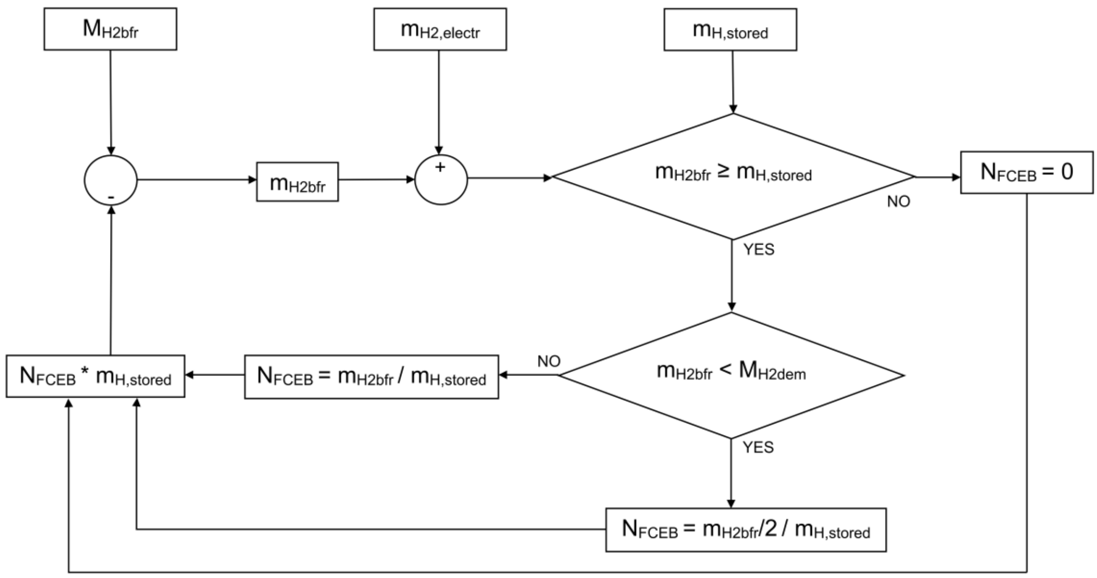



Fig. 5.1.9. Algorithm used to determine number of FCEBs to be refuelled daily.

### 5.1.2.4 Financial evaluation

Review of the financial parameters in relation to the proposed configuration plays a major part in the investment decision and the techno-economic analysis. In this context, the NPV, the IRR and PP of the project have been used to assess different investment scenarios.

For the calculation of the above parameters, a set of equations regarding all the different factors of the small-scale HRS business was used based on (Kuckshinrichs et al., 2016; Xydis, 2013b). The investment cost of the entire project is assumed to be covered by own capital and a bank loan (equity-loan ratio). Eq. 5.1.11, which includes the different components of the installation, indicates the formula for the calculation of the capital cost.

$$IC_o = IC_{WT}P_{WT} + IC_{el}P_{max} + IC_{CS} + IC_d + IC_{bfr}M_{H2bfr} + IC_{comp}P_{comp} + IC_{constr} \quad (5.1.11)$$

where $IC_o$ is the project's investment cost in €, $IC_{WT}$ is the total cost of the WT installation, $IC_{el}$ is the total cost of the electrolysis system, $IC_{CS}$ is the cost of the control and safety components, $IC_d$ is the cost of the dispenser, $IC_{bfr}$ is the cost of the $H_2$ buffer tank and $IC_{comp}$ is the cost of the $H_2$ compressor.

In addition, the total investment cost includes the construction and contingency (unexpected costs during construction work) costs ($IC_{constr}$), which can be estimated (see Eq. 5.1.12) as a percentage of the equipment cost ($f_{cost,constr}$ and $f_{cost,cont}$, respectively), excluding the wind turbine installation costs that have been taken into account in $IC_{WT}$ (Gim and Yoon, 2012).

$$IC_{constr} = \left(IC_{el}P_{max} + IC_{CS} + IC_d + IC_{bfr}M_{H2bfr} + IC_{comp}P_{comp}\right) * \left(f_{cost,constr} + f_{cost,cont}\right) \tag{5.1.12}$$

The low-pressure compressor for maintaining a pressure of 30 bar during the refuelling processes and a flow rate of approximately 200 $Nm^3/h$ is assumed to be a 3 kW ($P_{comp}$) compressor ideally used for hydrogen (RIX Industries, 2019).

For the calculation of the NPV of the project, the formulas found in Eqs. 4.2.37 and 4.2.38 were used (Kuckshinrichs et al., 2016; Xydis, 2013b). The parameters used to proceed with the financial evaluation of the project are found in Table E1, Appendix E. Table 5.1.2 presents the data used for the calculation of the investment cost of the proposed scheme.

The assumptions used in the financial evaluation included a project lifetime of 20 years ($n$), a bank loan with a repayment period of 10 years, an HRS workforce of one person for 13 hours per day and a required footprint of 1,000 $m^2$. Any form of subsidy in relation to the business plan is disregarded.

Subsequently, the calculation of the final cash flows during the operational lifetime of the project derived through the NPV formula results in an estimation of the IRR and the payback period.

In order to provide the best-case scenarios in relation to the project viability, a sensitivity analysis showing how IRR changes at different $H_2$ fuel costs and equity-loan ratios has been compiled.

### 5.1.3 Results and discussion

#### 5.1.3.1 Sizing of the HRS's components

As it was mentioned in the previous sections of this paper, the sizing of the WT powering the electrolyser depends on the final hydrogen demand for refilling the FCEBs as well as the wind resource of the investigated region. The results, which are based on Eq. 5.1.2 to 5.1.9, are presented in Table 5.1.2.

Table 5.1.2. Results of the WT sizing process.

| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Mass stored in the FCEB at 30 bar pressure | $m_{H,stored}$ | 5.465 | g |
| Estimated range of the FCEB with $m_{H,stored}$ of $H_2$ | $R_{bike}$ | 18 | km |
| Number of daily FCEB refills | $N_{bikes}$ | 1,149 | - |
| Maximum number of daily served FCEBs/hose | $N_{bikes,hose}$ | 480 | - |
| Number of HRS refuelling hoses | $N_{HRS,hoses}$ | 3 | - |
| Daily demand for hydrogen | $M_{H2dem}$ | 6.8 | kg |
| Annual energy production of the WT | $E_{WT}$ | 127,211 | kWh |
| Scale parameter of wind resource | $c_w$ | 6.495 | m/s |
| Shape parameter of wind resource | $k$ | 2.289 | - |
| Mean power coefficient | $\omega$ | 0.402 | - |
| Capacity factor | $CF$ | 0.298 | - |
| The WT's minimum rated power | $P_R$ | 48.4 | kW |

Based on Table 5.1.2, the WT's rated power should be more than 48.4 kW in order to satisfy the hydrogen energy demand of $N_{bikes}$. To this end, a H17.0-50kW wind turbine manufactured by Anhui Hummer Dynamo Co., Ltd. has been selected for the proposed configuration. The specifications are shown in Table 5.1.3.

Table 5.1.3. Specifications of the H17.0-50kW WT (HUMMER Industries, 2018).

| Parameter | Value | Units |
|---|---|---|
| Rotor diameter | 17 | m |
| Rated power | 50 | kW |
| Cut-in speed | 3.5 | m/s |
| Cut-out speed | 25 | m/s |
| Wind speed at rated power | 9.5 | m/s |

Fig. 5.1.10 presents the annual power generation of the WT based on the wind speed data shown in Fig. 5.1.6, the specifications of the proposed WT and the power curve given by the manufacturer.

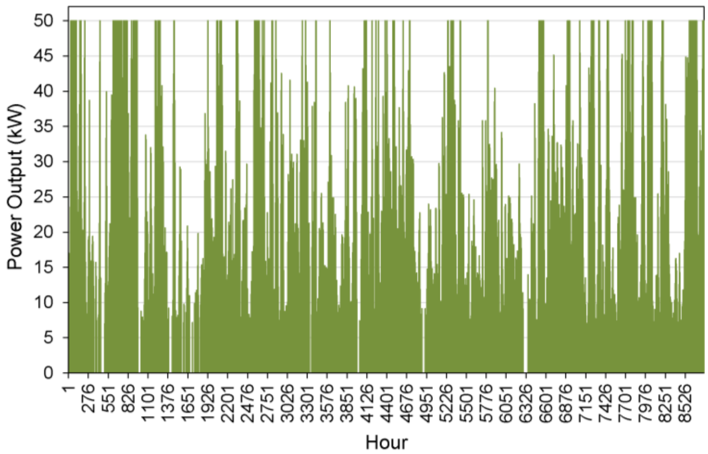



Fig. 5.1.10. Annual power output of the WT.

The sizing of the electrolyser is based on the algorithm presented in the previous sectopn (see Fig. 5.1.7). Fig. 5.1.11 indicates the number of electrolysers whose rated power was checked during the algorithm application. According to Fig. 5.1.11, a 70 kW capacity electrolyser is optimal for utilising the WT's generated energy to produce the largest quantity of hydrogen. 71.8% of the WT's available production is transformed into hydrogen. It is obvious that the capacity of electrolysis is higher than the one of the WT because of the electrolyser's operational power limits ranging between 10% and 100% of its nominal capacity.

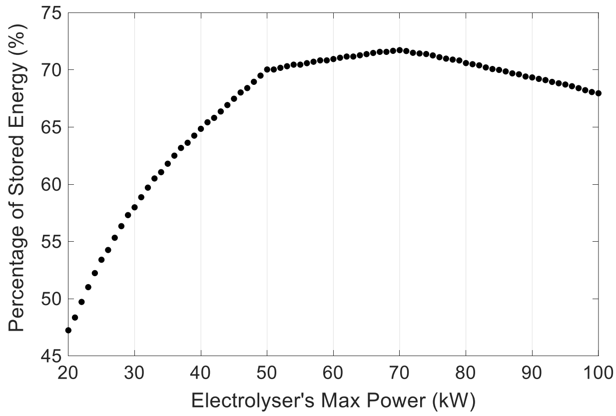



Fig. 5.1.11. The WT's stored energy percentage at different electrolyser's maximum operational power.

The daily hydrogen production ($m_{elH2}$) of the 70 kW electrolyser is depicted in Fig. 5.1.12. The maximum quantity produced per day reaches 21.2 kg, while the average daily production is calculated at 7.9 kg.

By comparing Fig. 5.1.10 and Fig. 5.1.12, one may observe that although the hydrogen production rate follows a similar pattern with the power output of the WT, there is an obvious difference when it comes to the maximum points. In many cases, when the WT's output power is maximum, the hydrogen production is lower than the expected 21.2 kg. This is happening because of the relationship between the operational temperature of the electrolysis and the electrolytic cell voltage (see Eq. 4.2.1 and 4.2.2). These equations suggest that even at similar power input values observed during a certain time period, the electrolyser does not produce the same amount of hydrogen when it operates under different temperatures. Fig. 5.1.13 illustrates the electrolyser's operational temperature variations on an annual, hourly basis. By comparing Fig. 5.1.12 and 5.1.13, it becomes apparent that the operational temperature of the electrolyser decreases whenever the power input is low, while when operating under maximum input, the temperature rises to the highest set value. However, this variation does not follow the power changes immediately because of the heat capacity and the thermal resistance of the electrolysis stack.

Thus, this phenomenon explains the differences observed between the $H_2$ production values at the highest values of power input.

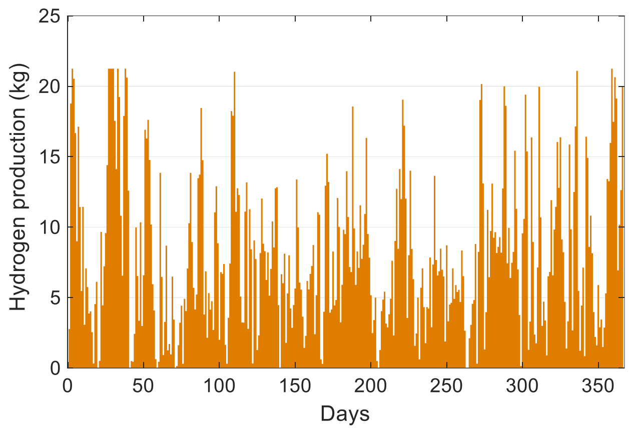



Fig. 5.1.12. Daily hydrogen mass production.

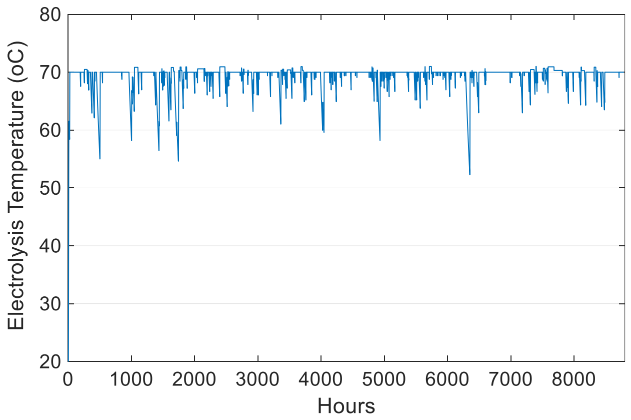



Fig. 5.1.13. Operational temperature of the electrolyser.

Regarding the hydrogen buffer storage tank, it should obviously be able to store the maximum daily $H_2$ produced by the electrolyser in order to avoid rejection of the produced hydrogen to the atmosphere. In this regard, and by taking into consideration that the maximum daily production of the electrolyser exceeds the daily demand (see Section 5.1.2.3, Table 5.1.2, and Fig. 5.1.12), the maximum $H_2$ mass that the tank should be able to store amounts to 21.2 kg. Hence, based on Eq. 5.1.1, the water volume of the $H_2$ buffer tank is calculated at 7.8 $m^3$.

By taking into consideration the daily hydrogen production and the buffer tank's water volume, the number of FCEBs that can be refuelled per day is shown in Fig. 5.1.14. Fig. 5.1.15 indicates the hydrogen mass rate inside the buffer storage tank when factoring in the number of daily refills.

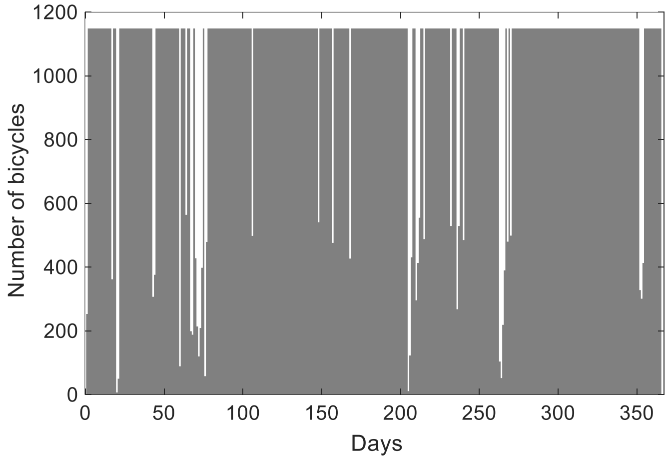



Fig. 5.1.14. Number of daily FCEB refills.

As is obvious, the daily demand for FCEB refills could not be covered entirely due to the intermittency of the wind-generated electricity. Based on the data from Table 5.1.2, the total annual demand for FCEB refuelling processes equals 419,385 refills. Instead, the proposed HRS would be able to cover the entire daily refuelling demand 322 times on an annual basis, while the total annual FCEB refills would reach 369,978.

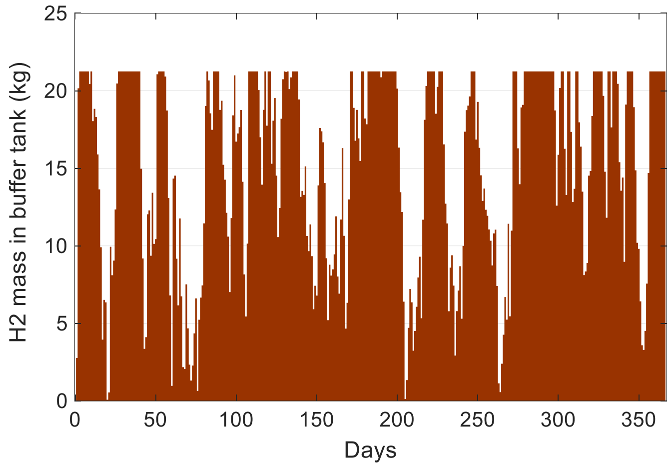



Fig. 5.1.15. $H_2$ annual mass flow rate in the buffer tank.

Consequently, in order to cover the total daily demand of the investigated region, implementation of at least one more HRS with lower capacity than the one investigated is required.

Table 5.1.4 summarises the results concerning the electrolysis process, the hydrogen buffer tank and the number of daily served FCEBs.

Table 5.1.4. Results of the electrolysis-buffer storage algorithm-FCEB refills.

| Parameter | Symbol | Value | Units |
|---|---|---|---|
| Electrolyser's maximum operational power | $P_{el}$ | 70 | kW |
| Electrolyser's maximum operational temperature | $T_{el}$ | 70 | °C |
| Number of electrolytic cells | $n_c$ | 54 | - |
| Electrolyser's maximum $H_2$ mass flow rate | $\dot{m}_{H2}$ | 0.24 | g/s |
| Calculated electrolyser's average overall efficiency | $\eta_{el}$ | 0.59 | - |
| Buffer tank's water volume | $V_{bfr,WV}$ | 7.8 | $m^3$ |
| Maximum $H_2$ buffer tank storage at 30 bar pressure | $M_{H2bfr}$ | 21.2 | kg |
| Annual hydrogen production | $M_{H2tot}$ | 2896 | kg |
| Average daily $H_2$ quantity stored in buffer tank | - | 15.1 | kg |
| Average daily refuelling processes | - | 1051 | - |
| Number of days of covered $H_2$ demand for refuelling in 1 year | - | 322 | - |

### 5.1.3.2 Financial results of the HRS

The economic viability of the proposed configuration is highly dependent on the equity-loan ratio and the price of the $H_2$ fuel. Fig. 5.1.16 shows the results of the sensitivity analysis concerning how IRR is affected by the $H_2$ fuel cost and the percentage of own capital in the initial investment.

The capital cost of the business plan, including the replacement of main electrolyser stack parts after the 10th year of operation, has been calculated at €248,130 from Eq. 5.1.11 and 5.1.12. Based on the results illustrated in Fig. 5.1.16, it is apparent that an $H_2$ fuel price above 50.2 €/kg$H_2$ is required in order to have a financially viable project. It can also be seen that even in the case of a lower equity-loan ratio (e.g. 20/80), the minimum price of hydrogen fuel is not lower than the above-mentioned value. Nevertheless, in this scenario, the IRR of the project would increase significantly should the $H_2$ prices increase only slightly.

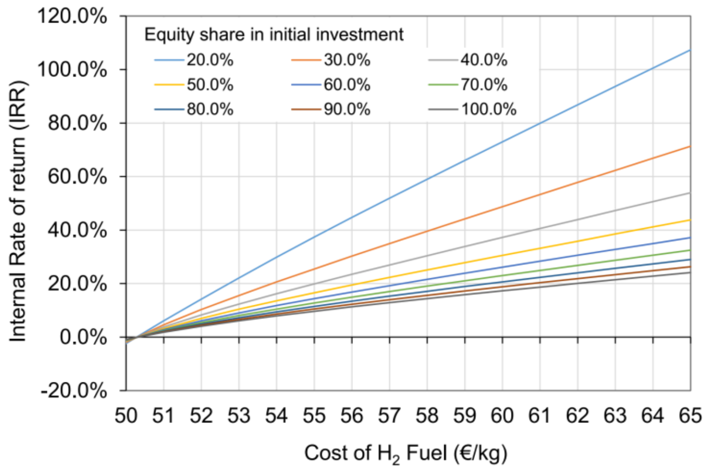



Fig. 5.1.16. Changes in IRR under different cost and investment scenarios.

Table 5.1.5 presents the NPV, IRR and PP for different costs of $H_2$ fuel under two different equity-bank loan ratio scenarios.

Table 5.1.5. HRS business scenarios at different $H_2$ fuel costs.

| | Equity-bank loan ratio 50/50 | | | Equity-bank loan ratio 20/80 | | |
|---|---|---|---|---|---|---|
| H2 fuel cost (€/$kg_{H2}$) | NPV (€) | IRR | PP (years) | NPV (€) | IRR | PP (years) |
| **51** | 25,860 | 3.19% | 12 | 26,203 | 6.11% | 12 |
| **52** | 61,764 | 7.00% | 10 | 62,107 | 14.20% | 6 |
| **53** | 97,668 | 10.41% | 8 | 98,011 | 22.13% | 5 |
| **54** | 133,572 | 13.57% | 7 | 133,915 | 29.85% | 4 |
| **55** | 169,476 | 16.58% | 6 | 169,818 | 37.37% | 4 |

As Table 5.1.5 suggests, the NPV values for each ratio scenario are almost the same for the same $H_2$ fuel price. However, the calculations show that in the case of a self-financing ratio of 20%, IRR is significantly higher, while PP is substantially reduced. Although the most profitable scenario for an investor would be to set a fuel price higher than 53 €/kg$H_2$, the price of the fuel should be as more as appealing to customers in order to support the transition to hydrogen-based urban transportation.

### 5.1.4 Conclusions

The scope of this study was the assessment of a small-scale autonomous HRS powered by wind energy, able to support a relatively small city's FCEB fleet. The research on this specific topic provides a tool for the estimation of the technical and financial parameters of a small-scale HRS coupled with an on-site wind turbine powering a water electrolysis system. The results indicate that this venture is feasible only by employing proper sizing and optimisation techniques in order to accommodate the daily hydrogen fuel demand, while keeping the cost of the station as low as possible.

In sum, the research results show that a medium-scale urban area with relatively good wind resources, such as the Herning municipality located in Denmark, can accommodate at least one HRS in a scenario where FCEBs would be the main transportation mean for urban trips. The proposed three-hose HRS would be able to support the daily demand for hydrogen fuel more than 87% of the annual calendar days, while no refuelling processes would occur in only one day of the year. From a financial point of view, the capital investment required for this type of HRS is not prohibitive for an investor, and the IRR in conjunction with the NPV and the PP presents positive results for an unsubsidised price of the $H_2$ fuel above 51 €/kg$H_2$.

Although this cost seems relatively high compared to previous researches for hydrogen production coupled to wind power (i.e. price up to 26.6 €/kg$H_2$), it is normal to observe this price increase due to the other components required for even a very small capacity HRS with relatively low hydrogen fuel annual demand. Additionally, the country of installation seems to play a significant role in the final price of the hydrogen fuel due to the labour, land costs and taxation schemes. To this end, it can be concluded that the hydrogen fuel price is dynamically calculated and compared to conventional fuels it could present higher volatility between countries.

In conclusion, this research consists of a feasibility assessment of the proposed solution in order to identify possible business opportunities for energy investors and contribute positively in the transition to a future hydrogen-based economy.

## 5.2 Assessing the operation and different refuelling cost scenarios of a fuel cell electric bicycle under low-pressure hydrogen storage

The transition to low- or zero-emission vehicles in the transportation sector is a challenging task toward meeting the greenhouse gas emission targets set by the majority of countries. One way of achieving this goal is to utilise hydrogen gas via fuel cell electric vehicles. This paper investigates the operation, driving range and refuelling process of a fuel cell electric bicycle. The methodology applied includes an estimation of the bike's range under different routes and riders, the riders' opinions and a financial evaluation of the hydrogen fuel cost compared to other urban vehicle alternatives. The results showed a minimum median range-to-energy consumption ratio of 20.5 km/kWh, while the maximum hydrogen cost was found to reach 0.025 €/km when refuelling the hydrogen bicycle in an autonomous hydrogen station. The outcome of this study indicates that the introduction of light-duty hydrogen vehicles in urban transportation may adequately meet the average daily driving distance of city residents.

### 5.2.1 Introduction

Since the beginning of the 1990s and especially after the treaty known as the Kyoto Protocol, many countries, including the EU, have set targets for reducing GHG emissions than the ones documented in 1990 (United Nations, 2019b). In 1990, global GHG emissions within the OECD countries were equal to approximately 20.3 Gt $CO_2$-eq, while in 2016, emissions had dropped to 18.8 Gt $CO_2$-eq (OECD, 2019a). In contrast, non-OECD economies such as China and the Russian Federation presented an increase of GHG emissions from 8.7 Gt $CO_2$-eq in 1990 to more than 16 Gt $CO_2$-eq in 2016, suggesting a cumulative increase of total emissions by 17% (Climate Action Tracker, 2019; Ge et al., 2016; OECD, 2019a).

In the EU, GHG emissions, including international aviation, have decreased significantly since 1990 (from 5.7 Gt $CO_2$-eq in 1990 to 4.5 Gt $CO_2$-eq in 2017), indicating that the member states have implemented policies promoting RES in sectors such as electricity production and the energy market in general (Eurostat, 2020a). The RES share in gross final energy consumption has increased from 8.5% in 2004 to 17.5% in 2017, while the targets for 2020 and 2030 have been set to 20% and 27%, respectively (Eurostat, 2019c; IRENA and European Commission, 2018). The evolution of GHG emissions by sector in the EU-28 since 1990, shows a clear reduction in the vast majority of the sectors, with the most obvious being the energy sector from 1.7 Gt $CO_2$-eq in 1990 to 1.2 Gt $CO_2$-eq in 2017. The only sector where GHG quantities has increased is in transportation (from 0.79 Gt $CO_2$-eq in 1990 to 0.95 Gt $CO_2$-eq in 2017) (Eurostat, 2020a).

Road transportation emissions in the EU-28 have increased from 0.73 Gt $CO_2$-eq in 1990 to 0.90 Gt $CO_2$-eq in 2017, while at the same time, the share of annual emissions from transportation has increased from 92% to 95%, respectively (European Commission and Directorate General for Mobility and Transport, 2018; Eurostat, 2020a).

Acknowledging the above, one can observe that road transportation and specifically urban mobility plays a significant role towards the target of reducing GHG in the near future. As seen in Fig. 5.2.1, light-duty vehicles such as private cars comprised 60.6% of the total GHG emissions of road transportation in 2017, suggesting that the adoption of a 'greener' way of transportation such as alternative-powered vehicles could be an important benefit in coping with high GHG emissions (Bekiaris et al., 2017; Eurostat, 2020a; Morrison et al., 2018). Moreover, the European Commission has estimated that more than 40% of $CO_2$ and 70% of other GHG emissions from road transportation are observed in urban environments due to the large traffic problems and the overpopulation (European Commission, 2019b).

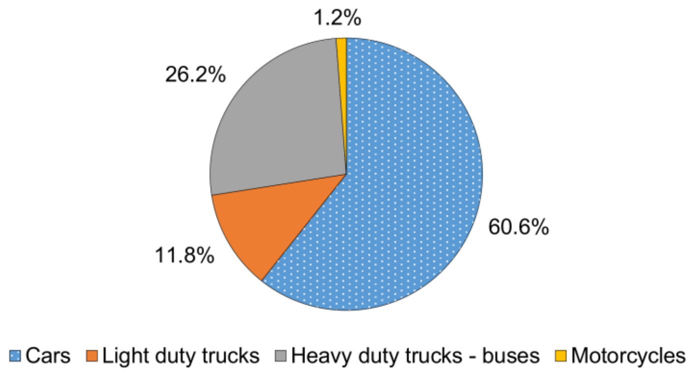



Fig. 5.2.1. Shares of road transportation vehicles in the EU-28 (2017). Based on (Eurostat, 2020a).

Contemporary alternative-powered vehicles presenting environmental benefits in a LCA include, among others, the BEVs and the FCEVs. Bicer and Dincer (2017) published a research study that compared alternative vehicle technologies in terms of LCA and concluded that the hydrogen vehicles presented an almost three times lower global warming potential than BEVs and methanol-fuelled vehicles (Bicer and Dincer, 2017). In this context, Shin et al. (2019) suggested that FCEVs can be more environmentally friendly than BEVs, especially in cases where the hydrogen fuel is supplied as a by-product of the chemical industry (Shin et al., 2019). Similarly, Thomas (2009) argued that in the near term, FCEVs would be more environmentally friendly than BEVs due to 1) the fossil fuel-based electricity mix of most countries, contributing to increased lifetime GHG emissions of BEVs and 2) the assumption that most of the produced hydrogen would come from natural gas reforming processes (Thomas, 2009). FCEVs introduction in the transportation fleet of the Turkish city of Burdur, replacing 10% of expected conventional vehicles by 2030 was assessed by Uyar et al. (2019). The results of their study indicated that even with this low penetration of FCEVs, $CO_2$ emissions in the specific region would decrease by 43.44 kt (Uyar et al., 2019). Likewise, Liu et al. (2020) studied the WtW energy and emission differences between FCEVs and internal combustion vehicles. The outcome showed that even if the hydrogen fuel is derived from fossil fuel processes, WtW energy and GHG emissions are lower by 5% - 33% and 15% - 45% respectively (Liu et al., 2020). However, according to Kolbe (2019), FCEVs fuelled by hydrogen produced from water electrolysis powered from a regular energy mix presented in general no environmental benefits compared to other alternative fuel vehicles (Kolbe, 2019). In this regard, Li et al. (2016) published a more detailed analysis comparing the environmental benefits of FCEVs and BEVs, respectively. The authors concluded that vehicles with greater environmental benefits depend on the energy mix, the methods used to produce the hydrogen fuel and the phase of the fuel (i.e. in gaseous or liquid form) (Li et al., 2016). One may also argue that depending on the energy mix and the respective electricity prices of each country, FCEVs might present higher driving costs compared to BEVs. Wu et al. (2019) developed an optimisation algorithm concerning the power allocation between the FC and the battery pack of a plug-in FCEV. The results showed that only the size of the FC system is affected by different driving styles, while the optimised battery pack system did not require any alteration. For a city driving cycle of a 50 kW FC rated power FCEV, hydrogen consumption and consequently fuel cost increased, while for a suburban driving cycle the energy cost decreased by approximately 52% (Wu et al., 2019). In the same context, Hu et al. (2020) investigated the energy management optimisation of a hybrid FC-battery bus aiming at a cost-optimal solution. The outcome of their study showed that hydrogen fuel along with FC and battery cost evolution affects significantly the optimisation result, while degradation of the FC and battery components seemed to slightly decrease the cost (Hu et al., 2020).

According to the above, the transition of the mobility sector in terms of road transportation to hydrogen-based light-duty vehicles would substantially benefit the environmental parameters found in urban areas with the least possible operating cost. To this end, this research focuses on the operating conditions, characteristics and refuelling processes of a light-duty FCEV in an urban environment such as a FCEB or a FCES. Although a FCEB cannot be considered entirely as a motor-based vehicle, it is a version of an electric bicycle that either uses a FC to direct power the DC motor to support the pedalling force of the rider or uses a FC extender to increase the driving range of the battery-based configuration. In this regard, FCEBs can be used extensively in urban environments for commuting purposes by replacing conventional non-environmentally friendly vehicles.

One may suggest that the main benefits of a FCEB/FCES over a battery-based bicycle/scooter are the same benefits of FCEVs compared to a BEVs. FCEVs present similar behaviour in terms of range autonomy and refuelling time such with the conventional vehicles, meaning higher driving range than battery-based vehicles and refuelling times that do not exceed 3 min (Brey et al., 2018). Similarly, a FCEB/FCES is expected to present significantly lower refuelling time than the recharging time of a battery bicycle/scooter, while depending on the respective system, driving range may be substantially higher. Thus, the aim of this paper is to investigate the prospects of FCEBs in the urban mobility sector.

The operation and prospects of light-duty hydrogen vehicles appropriate for transportation in city centres have been investigated by several researchers in the past, showing advantages and disadvantages compared to conventional or/and other alternative-powered vehicles. Colella (2000) studied the market opportunities of a low-power FCES in Thailand and concluded that at the time of the research publication, FCESs showed better performance than lead acid electric scooter counterparts, but technical obstacles such as drying of the FC's membrane or decreased efficiency during rapid acceleration should be overcome (Colella, 2000). The efficiency and operation of an electric bicycle with a FC extender were examined by Cardinali et al. (2002), showing an increase of the range from 25 to 120 km, while the system's efficiency was found to increase with power (Cardinali et al., 2002). In 2003, Tso and Chang published a plan for the implementation of FCESs in Taiwan in order to cope with the intensive environmental pollution found in big cities, while in 2012, Tso et al. presented the results of the experimental operation of a FCES fleet in Taiwan. The results showed drawbacks concerning the endurance of the drivetrain system and the effect of the ambient temperature to the system's performance, and revealed data on hydrogen fuel economy and range (Tso et al., 2012; Tso and Chang, 2003). Hwang et al (2004) designed, developed and studied the operation of a 300 W FCEB with metal hydride hydrogen storage. The road test data showed an efficiency between approximately 22% and 34% as well as a distance-to-fuel ratio of 1.35 km/g$H_2$ (Hwang et al., 2004). In 2009, Chao et al. (2009) presented a modelling and simulation algorithm of a FCES. The simulation of the system showed that the size of the fuel cell system should have a peak power of 3.6 kW and an average power of 600 W. The average hydrogen consumption was calculated to 1.6 $g_{H2}$/km (Chao et al., 2009). In 2011, Tang et al. published an experimental study of a 2 kW power FC system for lightweight vehicles. The research focused on the dynamic response of the FC system under load variations, and the authors concluded three main things from the study. Overshoot and undershoot of the FC current and voltage, respectively, were observed during the load variation due to the water and gas transport as well as the distribution inside the FC, while the FC's response was transient to power variations, and in case of higher loads than the ones the FC could support, the battery supported the system (Tang et al., 2011). Hwang (2012) reviewed previous research studies on FCESs and performed a SWOT analysis for the development of

FCESs in Taiwan by using as input the energy density and GHG emissions of FCESs compared to battery and conventional counterparts. In all cases, the FCES showed lower energy consumption and GHG emissions per kilometre in a WtW analysis compared to the other vehicles accounting for approximately 123 Wh/km and 23 g $CO_2$-eq/km, respectively, while the SWOT analysis revealed high prospects for the implementation of FCESs in Taiwan (Hwang, 2012).

Studies published recently show better driving and operating behaviour of contemporary light-duty FCEVs, indicating an established status of this technology. Kheirandish et al. (2014) investigated the operation of a FCEB comprising of a 250 W FC, a battery pack, a DC/DC converter and other auxiliary components. The results documented a FC average efficiency of 48.4% and a system's efficiency of 35.4%, which is much higher than that of a conventional vehicle (Kheirandish et al., 2014). Using a FC as a range extender of a BEV was assessed by Millo et al. (2016). The authors studied the a 1.3 kW FC to supply the accessory loads of the vehicle concluding that the BEV range could increase by 19%, if the hydrogen tank capacity would be 30 L at a pressure of 350 bar (Millo et al., 2016). In 2017, Mellino et al. published a LCA comparison of battery and FC electric bicycles. The evaluation of the LCA was based on a travelling range of 100 km for both vehicles, and the outcome showed that the production phase of the FCEB was more harmful to the environment due to the complexity of the components used. The battery electric bicycle, however, performed environmentally worse during the operating phase (Mellino et al., 2017). Another benefit of a light-duty hydrogen vehicle such as a FCES was presented by Robledo et al. (2019). The authors examined the utilisation of this vehicle type as a V2G or V2L application. The results showed that using a FCES for a V2L application degrades significantly the FC, while V2G application is more efficient. Moreover, the main conclusion was that although using a FCES as a grid or load support application in conjunction to the typical driving mode is feasible, a new energy management system would be required to be included in the topology (Robledo et al., 2019).

The hydrogen refuelling infrastructure in terms of FCEBs refuelling processes was studied by Kovač and Paranos (2019) and Apostolou et al. (2019). Kovač and Paranos (2019) presented the results of the operating factors for a 300 W FCEB with metal hydride hydrogen storage and the respective HRS design to produce hydrogen from solar energy. The authors concluded that the bicycle driving range was approximately 66 km with 4.5 g of hydrogen stored, while the proposed HRS with a $H_2$ outlet flow rate of 2000 cc/min could provide fuel for at least five bicycles totalling 100 km of driving range (Kovač and Paranos, 2019). Apostolou et al. (2019) developed an algorithm for the sizing and optimisation of a wind energy-powered on-site $H_2$ production refuelling station to cover the demand of FCEBs' fleet in urban environments. The authors also presented a financial analysis of the optimised autonomous-powered station showing a hydrogen price of approximately 50 €/kg$H_2$ in order to have an economically feasible investment (Apostolou et al., 2019). Similarly, Le Duigou et al. (2013) documented a hydrogen cost for an autonomous on-site HRS higher than the current retail price of hydrogen fuel for off-site HRSs in USA (14 \$/kg$H_2$ or 13 €/kg$H_2$ on average) (California Fuel Cell Partnership, 2020), reaching 17 €/kg$H_2$ (Le Duigou et al., 2013). Penev et al. (2019) on the other hand, argued that the hydrogen price in HRSs could reduce to 4.9 €/kg$H_2$ (5.2 \$/kg$H_2$) for large stations and fossil-fuel derived hydrogen. The respective cost for electrolytically produced and pipe delivered hydrogen would increase for the same HRS type to 11.4 €/kg$H_2$ (12.3 \$/kg$H_2$) (Penev et al., 2019).

Based on the aforementioned studies, it can be derived that although the technical assessment of FC light vehicles has been investigated to a certain degree, there is still a gap in knowledge regarding experimental analyses of different hydrogen refuelling processes and comparisons to other private transportation options. It is apparent that the fuel cost plays a significant role in the total operating costs of a vehicle aiming to penetrate an already existing market. Moreover, according to the operating behaviour of a light hydrogen vehicle, the major impact from the consumers' economical point of view still needs to be assessed.

Hence, in order to keep a less complex system and consequently have a low-level $H_2$ fuel cost, it has been decided to study the case of a FCEB, operating under low hydrogen gas pressure storage, which does not mandate the utilisation of a large compressor. Therefore, the objectives of this research can be stated by the following RQs:

RQ5.2.1: What is the average range-to-energy consumption ratio of a FCEB under low-pressure hydrogen gas storage?
RQ5.2.2: Is the refuelling cost and time of FCEBs/FCESs comparable to other means of private urban transportation?
RQ5.2.3: What is the riders' opinion on using the FCEB, and what is the fuel price they are willing to pay?

The structure of this paper consists of three main sections, including a description of the experimental configuration used to gather the required data, along with the methodology applied to analyse the data and elicit the results. Furthermore, the presentation and the assessment of the results are linked to the respective RQs: How/if the objectives of this study are met, what weaknesses might arise and what future research should focus on?

### 5.2.2 Materials and methods

Examining the above-stated RQs was based upon the experimental results of a range-to-energy ratio and other operating parameters such as riding time and average speed of the FCEB. The derived outcomes were analysed for three refuelling scenarios, and the corresponding levelised $H_2$ fuel cost-to-range ratios were compared to the respective values of other city-oriented vehicles found in peer-reviewed literature.

### 5.2.2.1 Equipment and refuelling configuration

The main equipment used during the stage of gathering the operational data of the FCEB included a commercialised 250 W motor FCEB (based on EU legislation), an alkaline electrolyte membrane water electrolysis and a hydrogen dryer system with a web interface able to connect to a personal computer. Through the web interface, the user can observe and log electrolysis parameters (i.e. $H_2$ flow rate, total $H_2$ production, $H_2$ pressure and temperature, stack voltage). Additionally, an energy logger was used to measure the energy consumption during the refuelling process of the hydrogen bike.

The power pack system of the FCEB comprised an air-cooled PEM FC supplied with $H_2$ gas from an on-board hydrogen tank through a pressure-regulating valve, a DC/DC converter/charger, a Li-ion battery and an electric motor. The components were connected in series meaning that the battery pack supplied the motor, and once its SOC dropped below a certain threshold, it was charged through the FC (see Fig. 5.2.2) (Pragma Industries, 2017). Hence, the PEM FC acts as a range extender of a normal BEB but with smaller battery capacity compared to common BEBs. Although this configuration compared to a direct connection between the PEM FC and the motor would act negatively in terms of energy efficiency and consequently driving range, the author decided to use the specific topology in order to assess the operation of the under investigation FCEB at its lowest possible performance.

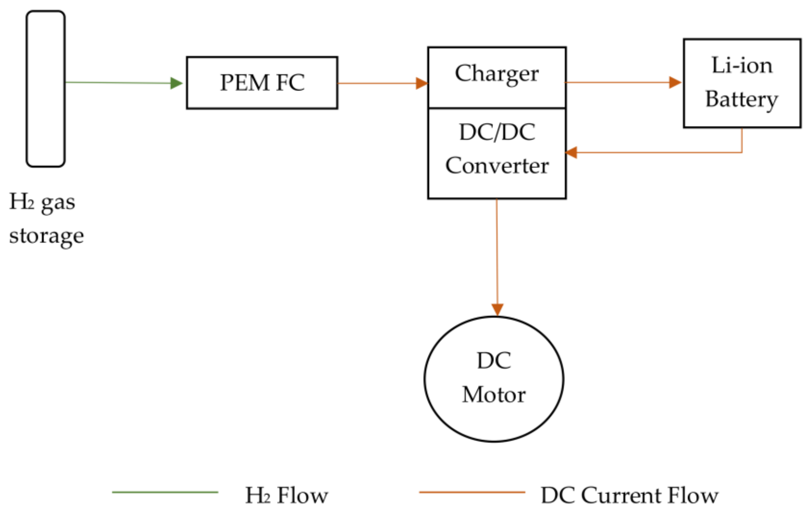



Fig. 5.2.2. FCEB energy flow topology.

The refuelling process was based on the electrolysis system, which was connected to the hydrogen dryer for increasing the $H_2$ purity to 99.999% as well as the inlet hose of the FCEB on-board hydrogen tank.

A hydrogen leak detector was used as a safety precaution. During the entire process, the energy consumption of the configuration was measured and logged. The refuelling process stopped automatically once the pressure inside the $H_2$ tank reached 30 bar.

In case the battery pack of the FCEB was discharged and no hydrogen was stored inside the on-board tank, the refuelling process would continue until the battery was charged from the operation of the bike's FC, using the hydrogen produced by the hydrogen generator.

The experimental arrangement and the technical specifications of the FCEB as well as the electrolysis system are depicted and summarised in Fig. 5.2.3 and Table 5.2.1, respectively.

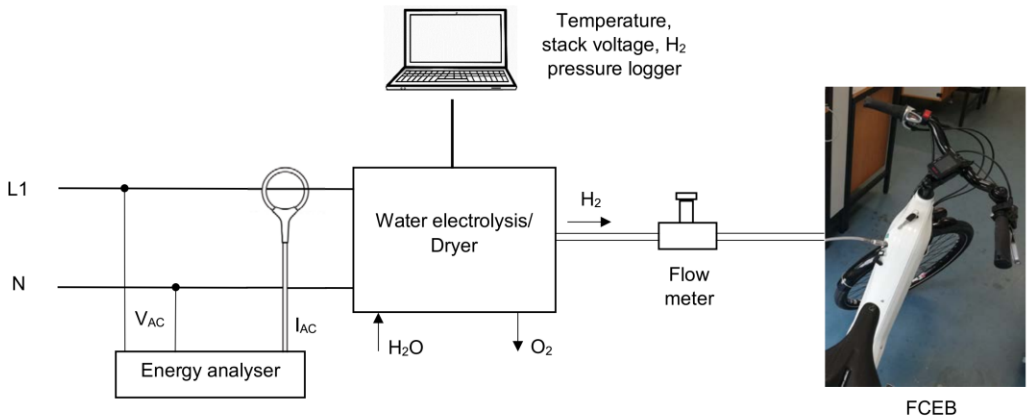



Fig. 5.2.3. The laboratory FCEB refuelling process.

Table 5.2.1. Specifications of the FCEB and the hydrogen production system (ACTA, 2014; Pragma Industries, 2017).

| Parameter | Value | Unit |
|---|---|---|
| **Fuel Cell Electric Bicycle** | | |
| Motor power | 250 | W |
| Motor voltage | 36 | V |
| PEM FC max. power | 150 | W |
| Max. tank pressure | 200 | bar |
| Internal tank volume | 1.9 | NL |
| Li-ion Battery capacity | 150 | Wh |
| **Hydrogen Production System** | | |
| Electrolyser max. power | 700 | W |
| Dryer's rated power | 200 | W |
| $H_2$ flow rate at 20 ºC and 1 bar | 100 | NL/h |
| Max. outlet $H_2$ pressure | 30 | bar |
| Max. operating temperature | 55 | ºC |
| Outlet $H_2$ purity | 99.999% | - |

### 5.2.2.2 Methodology

The general methodology employed in the research process can be divided into four sections and is depicted in Fig. 5.2.4. The first part of the methodology identified the routes (see Fig. 5.2.5) to be followed by the participants, who volunteered to ride the FCEB. The chosen routes were cycle paths of approximately 25 km with different inclinations. The experiments took place near the Municipality of Herning in Central Jutland, Denmark. Each volunteer chose to follow one of the two available routes.

The average frequency of positive and negative slope angles observed during a trip of the two routes was calculated to be 50.4% and 49.5% for Route 1 and 51.5% and 48.5% for Route 2, respectively. This suggests that there was a small deviation between the two routes, meaning that Route 2 needed more effort by the rider. To support this, an investigation of the observed frequency of slope angles above 20$^o$ (see Fig. C1 in Appendix C) indicated that Route 2 presented higher frequency compared to Route 1 (i.e. 106 times compared to 67 times). Additionally, Fig. C1 shows that in Route 2 there are more times with a positive slope compared to Route 1 (i.e. 2057 times compared to 1969 times respectively), suggesting that Route 2 can be considered more difficult during the biking process compared to Route 1.

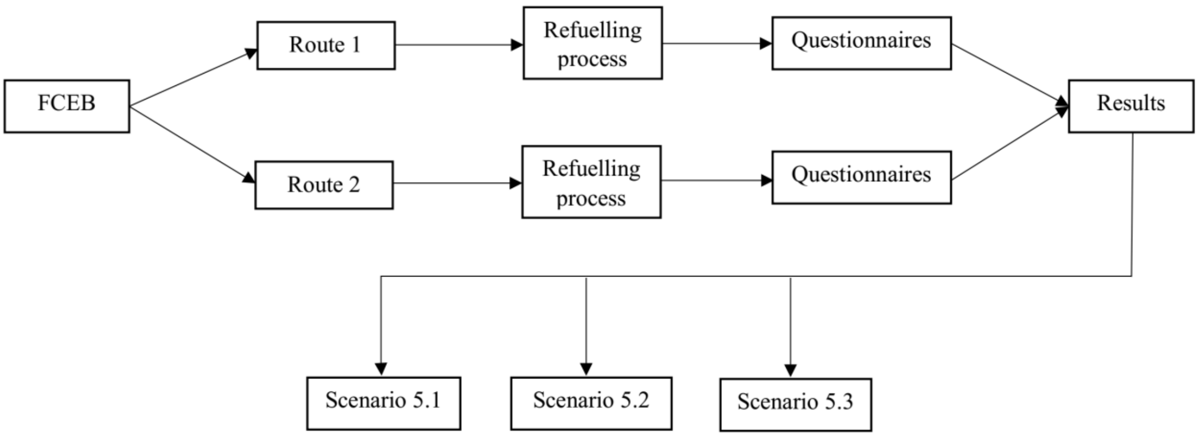



Fig. 5.2.4. General methodology employed.

The initial SOC of the FCEB was decided to be either full, meaning that the battery pack was fully charged, and the $H_2$ tank was filled with $H_2$ at 30 bar (case a) or partially discharged with a completely discharged battery pack and a full $H_2$ tank at 30 bar of pressure (case b). The reason for choosing these two cases was to examine how the FCEB behaves under the extreme condition of a discharged battery and under a more normal condition where SOC is 100% and $H_2$ gas is stored at 30 bar.


Fig. 5.2.5. FCEB routes used during the experiment.

Each riding process continued until there was no energy available in the FCEB's power system to support the pedalling effort of the participants. During the riding part, the range, speed of the vehicle, elevation and slope were measured in order to compare the data from the different riding styles of the volunteers. The FCEB has the ability to operate under three riding modes (i.e. cruise, tour and sport). The chosen mode for all participants was set to 'sport' to determine the maximum energy consumption. The weather conditions during the rides were not considered, because 1) the results should be as close to real-life cases as possible, and 2) results obtained under the same environmental conditions would be non-comparable due to the different riding styles of the participants.

The next stage of the methodology involved the refuelling process of the FCEB and was described in the previous section of this paper. The third section of the methodology comprised the analysis of the data derived from the two routes that the volunteers had followed as well as the recharging phase of the bicycle. A questionnaire (see Appendix D) based on the data from each route was given to the volunteers, who answered the questions, stating their personal opinions. A descriptive statistics of the questionnaire's qualitative data and the quantitative data received from the route and hydrogen production measurements were analysed in order to find possible interactions between the results. The first three parts of the methodology focused on providing enough information to answer RQs 5.2.1 and 5.2.3.

The last stage of the methodology was to answer RQ5.2.2. Three SCs of refuelling the FCEB via on-site hydrogen production schemes were analysed, and the outcomes were compared to respective values found in literature for different vehicles used in urban environments. The vehicles used to compare the results of the FCEB included a FCES, a BEB (based on EU legislation), a BES, a BEV, a petrol scooter, a small petrol car and a small diesel car.

SC5.2.1: The relevant quantitative data gathered from the previous parts of the experiment based on the refuelling process via the small-scale laboratory electrolyser supplied by the main electrical grid were used to compare respective values of other vehicle technologies.

SC5.2.2: Data presented by Apostolou et al. (2019) concerning the $H_2$ fuel retail price of an autonomous on-site hydrogen production HRS for light FC vehicles were used to compare other vehicles (Apostolou et al., 2019). Based on the results of Apostolou et al. (2019), it should be also noted that this price corresponds to similar conditions as case (b) where the buffer battery of the FCEB is assumed to be fully charged. In the context of case (a), where the fuel demand would be higher, the fuel price would be expected to be increased due to higher investments costs arising from the oversize of the WT and electrolysis systems in order to cover the increased demand. In this study, the same price of hydrogen fuel was used for both cases in order to find the minimum hydrogen cost that could be achieved in an autonomous HRS by covering the least hydrogen fuel demand.

SC5.2.3: The results of Apostolou et al. (2019) were modified to exclude the wind turbine powering the on-site hydrogen production and assume supply from the main grid (see subsection 2.2.1). The $H_2$ fuel price was then compared to the counterpart vehicles (Apostolou et al., 2019).

#### 5.2.2.2.1. Financial evaluation of an HRS for FCEBs with a hydrogen storage pressure of 30 bar

An autonomous HRS for the support of a FCEBs fleet in the Danish city of Herning has been proposed by Apostolou et al. (2019). To have a profitable business scenario, the authors calculated that the retail price of hydrogen should be at least 50.2 €/kg$H_2$ (applied in SC5.2.2). However, this value takes into account the cost of the wind turbine powering the hydrogen generator (Apostolou et al., 2019). SC5.2.2 concerns a similar HRS but with input power to the electrolysis system coming from the main electric network as well as real experimental data on the bike's autonomy and hydrogen consumption that are used to size the water electrolysis and $H_2$ storage systems. The main components of the proposed HRS are comprised of an electrolysis system, a low-pressure hydrogen storage system, a 30 bar hydrogen compressor, two hydrogen dispensers and other auxiliary systems (Apostolou et al., 2019).

The sizing of the alkaline electrolysis was based on the average daily hydrogen demand ($M_{H2,dem}$) that can be calculated from the maximum number of the FCEBs ($N_{bikes}$) served by the station on a daily basis and the $H_2$ quantity stored inside the bike's tank ($m_{H,stored}$) (see Eqs. 5.2.1 and 5.2.2). To estimate the maximum number of FCEBs served by one station, it is assumed that the station operates continuously between 8:00 AM and 9:00 PM. The time of the refuelling process at 30 bar depends on the hydrogen outlet flow rate of the compressor, which, in this case, is taken to be approximately 80 $Nm^3/h$ or 1.3 $Nm^3/min$ (RIX Industries, 2019). This means that theoretically, the bike's $H_2$ tank (i.e. 1.9 NL water volume) would take less than a minute to be filled. However, according to the manufacturer, the refuelling process time should not be less than one minute, and, thus, it is assumed that the process would last for one minute (Pragma Industries, 2017). '$N_{refuel}$' represents the number of refuelling processes per hour.

$$M_{H2,dem} = N_{bikes} * m_{H,stored}, \tag{5.2.1}$$

$$N_{bikes} = h_{operat} * N_{refuel}, \tag{5.2.2}$$

Knowing the average daily hydrogen flow rate demand (calculated by daily mass demand, operating hours and the specific density of hydrogen) and combining it with the nominal flow rate of commercialised water electrolysers, the maximum operational power rate of the electrolyser can be estimated. The low-pressure $H_2$ tank was sized accordingly to the average daily hydrogen demand, and the water volume of the tank can be calculated by using the specific density of hydrogen and Boyle's law (see Eq. 5.2.3) (Webster, 1963).

$$p_1 * v_1 = p_2 * v_2, \tag{5.2.3}$$

Proceeding to the financial evaluation of the HRS for SC5.2.2 and the estimation of the $H_2$ fuel cost for refuelling the FCEB, the NPV and the IRR of the project in 20 years (n) of operation were calculated. The hydrogen cost was set to a value where NPV and IRR presented positive numbers. To calculate the NPV, Eqs. 4.2.37, 4.2.38, and 5.2.4, 5.2.5 presented below were based on (Apostolou et al., 2019; Kuckshinrichs et al., 2016; Xydis, 2013b) and data from Table E1, Appendix E.

$$IC_o = IC_{el}\,P_{max} + IC_{CS} + IC_{comp}\,P_{comp} + IC_{bfr}\,M_{H2,bfr} + IC_d + IC_{constr} \tag{5.2.4}$$

$$IC_{constr} = (IC_{el}\,P_{max} + IC_{CS} + IC_{comp}\,P_{comp} + IC_{bfr}\,M_{H2,bfr} + IC_d) * (f_{cost,constr} + f_{cost,\,cont}) \tag{5.2.5}$$

### 5.2.3 Results

The objective of this research expressed through the aforementioned RQs is supported from the result section, which is divided into two main sub-sections (i.e. 5.2.3.1 and 5.2.3.2). The first sub-section concerns the analyses of the quantitative and qualitative data acquired during the experimental process and the subsequent answered questionnaires, while the second sub-section, presents the comparison results between the above-mentioned investigated SCs.

**5.2.3.1 FCEB refuelling and riding process results**

The first part of the research investigated RQs 5.2.1 and 5.2.3. For the two examined cases of refuelling the FCEB's on-board hydrogen tank under 30 bar of pressure (i.e. fully charged and discharged battery respectively) 16 participants volunteered (see Table F1, Appendix F) to follow the specified routes and subsequently answer a questionnaire. Ten of them participated in the first examined case, while the rest participated in the second case. Table F2 of Appendix F includes the quantitative data regarding the refuelling and riding processes for both cases. The 'Energy consumption' column represents the energy consumed during the electrolysis process, and the '$H_2$ consumed' includes the values of the consumed hydrogen during the battery's full charging and riding processes in case (a) and for the riding process alone in case (b).

Fig. 5.2.6 presents the range-to-energy consumption ratios results for both routes for cases (a) and (b).

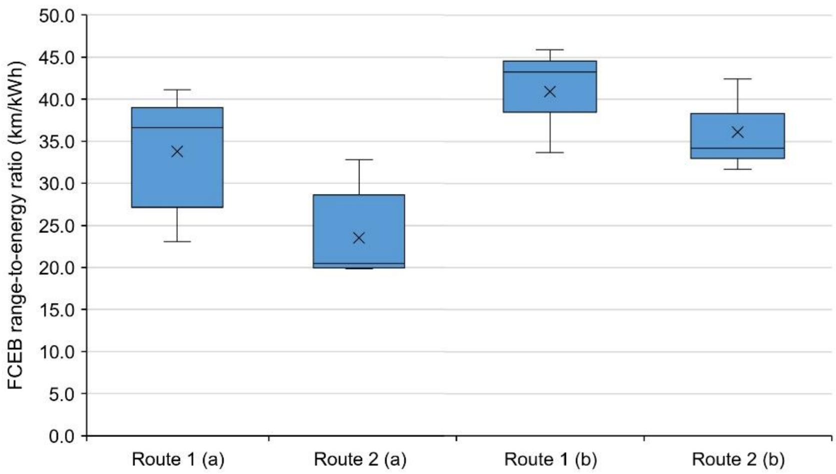



Fig. 5.2.6. Range-to-energy consumption ratio during the FCEB experiment.

The derived results show that the FCEB for the first case had a range of approximately 22 and 37 km depending on the route and the riding pattern that each rider followed. For the second case, the range of the FCEB is measured to be lower, i.e. between 13 and 18 km, which seemingly depends on the gender of the participant, where for male riders, the bike's autonomy was lower than for female ones.

The ratio of the range-to-energy consumption (see Fig. 5.2.6) of the refuelling process of the bike indicates that in both cases, the autonomy of the FCEB ranged between approximately 20 and 46 km per kWh of electricity consumption. The mean values for Route 1 have been calculated to 33.8 and 40.9

km/kWh for cases (a) and (b), respectively, while for Route 2, the mean ratios are found to be lower at 23.5 and 36.1 km/kWh, respectively.

Fig. 5.2.6 also provides information on the median, quartile ranges and values outside the interquartile range. According to the figure, the mean for Routes 1 and 2 for case (a) are 33.8 and 23.5 km/kWh, respectively. For Route 1, 25% of the experimental data present values between 23.1 and 27.1 km/kWh, 50% of the data demonstrate values between 27.1 and 39.0 km/kWh, while the last 25% shows values between 39.0 and 41.1 km/kWh. The median value is calculated to 36.6 km/kWh. For Route 2, the derived data show a median value of 20.5 km/kWh, while 25% of the data show almost the same values at 20 km/kWh, 50% between 20 and 28.6 km/kWh and the final 25% between 28.6 and 32.8 km/kWh.

In contrast, the data for Route 1 in case (b) are between 33.7 and 45.9 km/kWh with a median value of 43.3 km/kWh, while, similarly, the data for Route 2 are between 31.7 and 42.4 km/kWh with a median value at 34.2 km/kWh.

Based on the results, it is apparent that in case (b), the FCEB operates more efficient. This is happening due to the recharging phase of the battery through the FC (case a), which results to a lower efficiency of the FCEB operation. According to Table F2, the average hydrogen quantity used to fully recharge the on-board battery pack of the FCEB is calculated to 9.8 $gH_2$ accounting to approximately 326.3 Wh (based on the hydrogen's low heating value). So, by taking into account the FCEB battery pack capacity (see Table 5.2.1), the efficiency of the battery charging phase is estimated to 45.9%. In this context, Table F3 indicates that the mean energy consumption to range ratios for cases (a) and (b) are 0.038 and 0.026 kWh/km respectively. Case (a) has 46.1% higher energy requirements per km compared to case (b), which is similar to the energy lost during the recharging battery phase of case (a).

After the experiment, the volunteers were asked to participate in a survey including questions (see Appendix D) based on the data presented in Table F2, Appendix F. A descriptive statistics analysis of the questionnaires is presented in Table F4, Appendix F and Fig. 5.2.7.

For the descriptive statistics results, the presented numbers correspond to the available answers participants could give (see Appendix D). For the FCEB behaviour, 1 corresponds to 'Positive', 2 to 'Negative' and 3 to 'Neutral'. A 10-point rating scale was used for the driving experience, where 1 indicates 'Acceptable' and 10 'Excellent'. For the refuelling cost, 1 corresponds to '1 DKK (0.134 €)', 2 to '5 DKK (0.668 €)', 3 to '10 DKK (1.339 €)', 4 to '50 DKK (6.696 €)' and 5 to 'Other'. Finally, for the distance the volunteer is willing to travel in order to refuel the FCEB, 1 corresponds to '< 1 km', 2 to '1 km', 3 to '2 km', and 4 to 'Other'.

Fig. 5.2.7 indicates the frequencies of the acquired answers from the questionnaires.

The median values found in Table F4 are in alignment with the depicted data in Fig. 5.2.7, while the standard deviation of the questions represented by the table's columns indicates that most of the acquired data are close to the mean values.

The skewness values show how the distribution of the results is skewed. The positive values found in columns 1, 3, 4 and 5 of Table F4 depict a right-skewed distribution (i.e. most of the distribution is on the left part of the values), which can also be observed in conjunction with Fig. 5.2.7. In contrast, question 2 (column 2 in Table F4) has a distribution skewed to the left, showing that most data are closer to the left part of the distribution (i.e. 8 on the scale). The standard error of skewness shows that it is most likely that in a large population sample, the skewness tends to remain positive for questions 1 and 4 (columns 1 and 3), while for the other questions, the skewness can be oriented in either direction. Similar to the above, the standard error of kurtosis combined with the kurtosis values cannot give any conclusion about what would be the kurtosis in a larger sample.

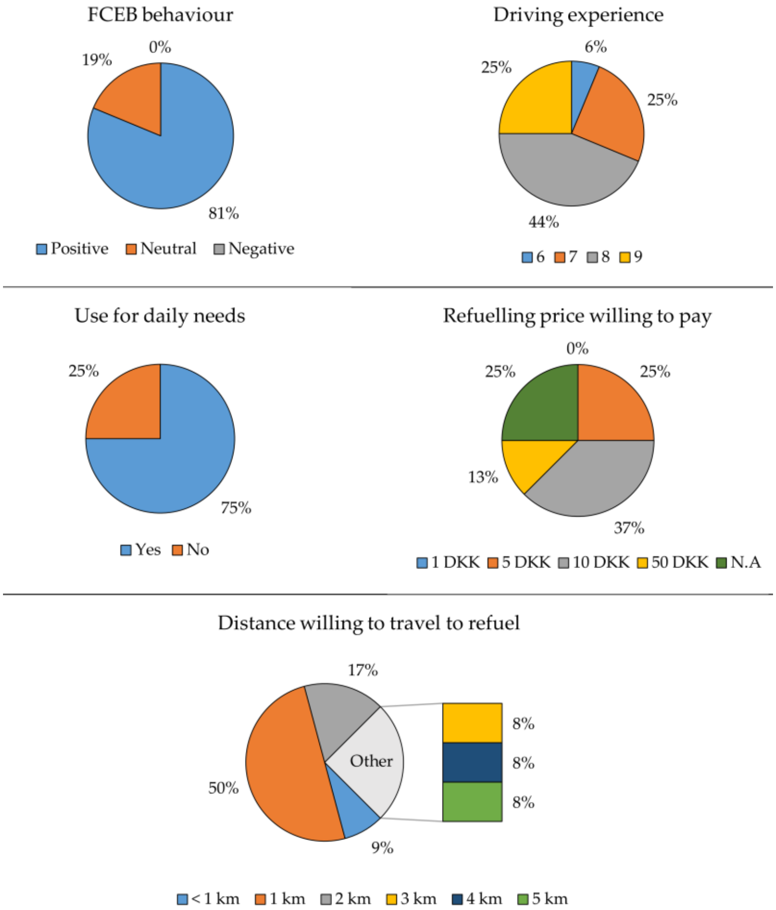



Fig. 5.2.7. Frequencies of the acquired answers from the experiment participants.

Conversely, according to Fig. 5.2.7, it is apparent that most of the participants (>80%) had no negative opinion of the FCEB; in fact, approximately 70% assessed their experience close to 'Excellent'. This is also supported by the fact that 75% of the volunteers stated that they could use this type of vehicle for their everyday obligations in an urban environment. The 25% of the participants who answered 'No' stated as reasons problems such as no coverage during bad weather phenomena or preferring a sport riding style more than the one the FCEB is able to provide. The latter can be considered as a normal feature of two-wheel electric bicycles, which according to EU legislation, provide torque assistance from the motor when bike's speed is up to 25 km/h (European Committee for Standardization, 2017). Higher speeds observed in an exercise riding pattern are compromised after 25 km/h by the lack of assistance and the larger weight of electric bicycles. Hence, one may suggest that this kind of electric bicycle is more suitable for commuting purposes such as going to work, the grocery store, or using it for normal touring activities. The majority of the participants who answered 'Yes' in question 4 (column 3 of Table F4) declared that the amount of money they are willing to pay for refuelling the FCEB would be between 5 and 10 DKK (0.668 and 1.339 €, respectively), with the most prevailing being the 10 DKK ('N.A' corresponds to participants answered 'No' in question 4 (column 3)). What is also noticeable is that 59% of the volunteers participating in both experimental cases (a and b) indicated the necessity to have hydrogen fuel available no more than 1 km away from their base, while another significant 24% mentioned distances above 3 km.

#### 5.2.3.2 Results of the investigated scenarios

The financial evaluation of the cost of hydrogen gas fuel involves the investigation of three scenarios mentioned in the previous section of this paper. These scenarios aim to provide results in relation to RQ5.2.2 by assessing refuelling costs and time of different commercialised vehicle technologies that can be used in urban environments (e.g. bicycles, scooters and small cars). In these scenarios, the data gathered from the experimental phase of the laboratory refuelling process along with the ones calculated for SCs 5.2.2 and 5.2.3 were compared with the data found in Table F6, Appendix F, showing the cost of fuel/energy per kilometre and the respective refuelling/recharging time of the vehicles. The cost of fuel/energy per kilometre is indicative for Denmark in order to be able to compare the technologies with the results derived from the experimental data. In the case of FCES, the vehicle's specifications (see Table F5) were based on the research compiled by (Hwang, 2012; Tso et al., 2012). The hydrogen storage comprised of two metal hydride replaceable tanks of total capacity 1000 NL and the refuelling pressure was set to 10 bar. The FCES topology does not include a battery pack, indicating that the PEM FC powers directly the DC motor through power electronics. Hence, the refuelling cost of the FCES was based on the same hydrogen refuelling methods and analyses of the FCEB case (b) where no initial recharging battery process is involved.

#### 5.2.3.2.1. Scenario 5.2.1

The first investigated scenario compares the acquired experimental data on the refuelling cost per km and refuelling time of the FCEB with the respective data of the alternative vehicles found in Table F6, Appendix F. To be able to compare the aforementioned data, a descriptive statistics analysis of cases (a) and (b) concerning the refuelling time as well as the ratio of the energy consumed during the production and storage of hydrogen fuel at 30 bar of pressure and the FCEB range was conducted. The results for both cases can be seen in Table F3, Appendix F.

The standard deviation of the two categories for both cases can be considered low, showing that the measured data do not deviate significantly from the mean values. Skewness for case (a) indicates that for the energy consumption to range ratio as well as the refuelling time, the distribution is highly skewed to the left of the values, i.e. closer to the mean. Additionally, the standard error of skewness shows that a larger sample would give a positive number of skewness. In case (b), the median and mean values are almost similar, while the skewness of the energy consumption to range ratio is positive, and the refuelling time equals to zero, showing a normal distribution. The standard error of skewness indicates that with a larger sample, skewness would probably remain positive.

In this context, it is valid to assume that for case (a), the data of energy consumption to range ratio and refuelling time are estimated to 0.038 kWh/km and 1.76 h, respectively. Similarly, for case (b), the respective estimated values are 0.026 kWh/km and 0.55 h. According to Table F2, the mean energy consumption to hydrogen consumed ratio for case (b) is estimated to 0.084 kWh/g$H_2$. So, by taking into account the average hydrogen consumption per km of the FCES (Table F5), the energy consumption to range ratio is estimated to 0.16 kWh/km. The time to refill the 1000 NL metal hydride canister of the FCES from the electrolyser used in this SC (see Table 5.2.1), can be estimated to approximately 10 h.

By taking into account the electricity cost in Denmark for household consumers equalling 0.31 €/kWh, the refuelling cost per km for the FCEB for cases (a) and (b) is calculated to 0.012 €/km and 0.008 €/km, respectively, while for the FCES this cost is estimated to 0.049 €/km. Hence, according to the respective values found in Table F6, it seems that for the first scenario, the refuelling cost of the FCEB is approximately 1.5 to 2 times higher than that of a BEB, while compared to other city-oriented vehicles, FCEB refuelling cost is 3 to 10 times lower. Regarding the FCES, the refuelling cost is similar to a normal petrol scooter and 1.5 times higher than the BES. The refuelling time in both examined cases for the FCEB is significantly higher than the refuelling time for conventional vehicles due to the low nominal flow rate (i.e. 100 NL/h or 8 g$H_2$/h; see Table 5.2.1) of the laboratory's electrolysis unit. However, compared to the recharging process of a battery-powered vehicle, it is approximately 5 times less. Likewise, the FCES recharging process time is significantly higher compared to all the other vehicles due to the low hydrogen outlet flow rate of the electrolyser and the larger than the FCEB tank capacity. However, based on the fact that the metal hydride tanks of the FCES are replaceable, the refuelling time could be done in minutes depending on the availability of filled canisters.

**5.2.3.2.2. Scenario 5.2.2**

The investigation of SC5.2.2 is based on the data presented by (Apostolou et al., 2019) compared with the data found in Table F6, Appendix F. According to Apostolou et al., the cost of hydrogen fuel, stored at 30 bar of pressure, of an autonomous on-site HRS powered from a wind turbine is calculated to 50.2 €/kg$H_2$ in order to have a feasible business scenario.

By taking into consideration the statistical analysis results for the hydrogen quantity consumed to the range of the FCEB ratio in cases (a) and (b), presented in Table F3, Appendix F, the cost per km can be calculated by Eq. 5.2.8.

$$\text{Priceratio}_{H2} = 50.2 * m_{H2,stored} / R_{FCEB} \tag{5.2.8}$$

The obtained data from the statistical analysis show a very low standard deviation for the hydrogen mass to FCEB range ratio in both cases. The positive low values of skewness show a slightly higher distribution of the values at the left part of the values' range. Hence, it can be assumed that the experimental data used in Eq. 5.2.8 regarding the FCEB's $H_2$ mass to range ratio are for cases (a) and (b) 0.0005 kg$H_2$/km and 0.0003 kg$H_2$/km, respectively. Furthermore, based on Table F5, the FCES's $H_2$ mass to range ratio is 0.0019 kg$H_2$/km.

Thus, according to Eq. 5.2.8, the cost per km for the FCEB refuelling process in SC5.2.2 equals to 0.025 €/km and 0.015 €/km for cases (a) and (b), respectively. Similarly, the cost per km for the FCES is calculated to 0.095 €/km. By comparing the derived results of SC5.2.2 with the respective values of the urban vehicle counterparts, one can comprehend that the refuelling cost of the FCEB is lower than all the alternative vehicles except the BEB, where its recharging cost per km is 2.5 to 6 times lower. In contrast, the refuelling cost of the FCES is 1.2 to 16 times higher than the other urban vehicles.

The refuelling time for the FCEB in SC5.2.2 is based on the flow rate of the $H_2$ compressor, which is 1.3 $Nm^3$/min (RIX Industries, 2019), and the water volume of the on-board $H_2$ tank (i.e. 1.9 NL) with a refuelling time for case (b) of less than one minute. In contrast, hydrogen gas is also used to recharge the battery to SOC 100% in case (a). Based on the data found in the '$H_2$ consumed' column in Table F2, Appendix F, the median value for both cases (a) and (b) concerning the consumed hydrogen mass has been found to be 15.1 and 4.8 $gH_2$, respectively. In other words, when comparing the two mass quantities, one may assume that to fully charge the battery pack in case (a), the on-board hydrogen tank should be filled two more times than in case (b). This number again is very low compared to the nominal flow rate of the compressor, and thus, the total refuelling time is maximum one minute. However, the charging process of the 150 Wh battery is based on the operation of the 150 W FC (see Table 5.2.1). Therefore, the time to recharge the battery would last for approximately one hour. To this end, the refuelling time for case (b) is highly comparable to the conventional vehicles, while for case (a), it is significantly longer but substantially lower than that of a battery-powered vehicle.

In the case of the FCES, the refuelling time of the 1000 NL storage capacity can be occurred in less than one minute. However, due to the metal hydride storage technology used in the FCES, high hydrogen inlet flow would result to an increased released heat of the metal hydride which would affect negatively the storage capacity. Lototskyy et al. (2017) documented an amount of 8 MJ of heat released during the process of storing 0.9 $kgH_2$ in a ‘low temperature’ metal hydride (Lototskyy et al., 2017). The authors reported that for refuelling this hydrogen quantity in 10 min, it is required to use a 13 kW cooling system. The fact that the proposed by Apostolou et al. (2019) HRS did not include a cooling system for metal hydride storage, it can be assumed that by reducing the hydrogen inlet flow to avoid the necessity of a cooling system, the refuelling time of the FCES could be 3 – 5 hours for getting the full metal hydride storage capacity. Therefore, in SC5.2.2, the FCES refuelling time would be similar to the time required to charge the battery-based vehicle counterparts.

#### 5.2.3.2.3. Scenario 5.2.3

The investigation of SC5.2.1 is based on a similar on-site HRS for light-duty FC vehicles to the one examined in SC5.2.2, but using the electrical grid instead of a wind turbine to power the hydrogen production unit. Following the methodology described in subsection 5.2.2.2.1, the electrolysis system’s maximum operating power can be estimated according to the daily demand of hydrogen fuel for the FCEB. The hydrogen mass used to refuel the FCEB (see Eq. 5.2.1) can be derived from the median values of the ‘$H_2$-consumed’ data mentioned in section 5.2.3.2.2. Consequently, based on Eqs. 5.2.1, 5.2.2 and 5.2.3, the daily hydrogen demand along with the respective electrolysis flow rate demand and the storage tank water volume are calculated and presented in the following table (Table 5.2.2).

Table 5.2.2. Results of sizing the electrolysis and hydrogen storage systems for refuelling FCEBs.

| | **Case (a)** | **Case (b)** |
|---|---|---|
| $h_{operat}$ (h) | 13 | 13 |
| $m_{H2,stored}$ (g) | 15.1 | 4.8 |
| $M_{H2,dem}$ (kg) | 23.6 | 7.5 |
| Electrolyser flow rate ($Nm^3/h$) | 20.1 | 6.4 |
| Electrolyser energy consumption ($kWh/Nm^3$) (NEL ASA, 2019) | 6.0 | 6.8 |
| Electrolyser max. power (kW) | 120 | 44 |
| Volume of buffer $H_2$ tank ($Nm^3$) | 8.6 | 2.7 |

Acknowledging the above, the capital cost of the proposed HRS for both cases (a) and (b) has been calculated by using Eqs. 5.2.4 and 5.2.5 to €263,193 and €136,170, respectively. In order to calculate the cost of hydrogen fuel for both cases, Eqs. 4.2.37 and 4.2.38 have been used to determine at what fuel price the NPV and IRR would present positive values. The results were based on an equity/bank loan ratio for the investment of 50/50. The assumptions used during the financial analysis included a project lifetime of 20 years and a bank loan with a 10-year repayment period. The workforce for operating the HRS was assumed to be two and one individuals as well as a required footprint of 500 and 300 $m^2$ for cases (a) and (b), respectively. No subsidies related to the business plan were taken into consideration. The results for both cases are presented in Table 5.2.3.

Table 5.2.3. HRS financial evaluation at different costs of $H_2$ fuel.

| **Case (a)** | | | **Case (b)** | | |
|---|---|---|---|---|---|
| $H_2$ fuel cost (€/kg$H_2$) | NPV (€) | IRR | $H_2$ fuel cost (€/kg$H_2$) | NPV (€) | IRR |
| 21.9 | -14,869 | -1.85% | 32.5 | -6,565 | -1.05% |
| 22.0 | -4,190 | -0.52% | 32.6 | -3,171 | -0.50% |
| 22.1 | 6,490 | 0.81% | 32.7 | 222 | 0.03% |
| 22.2 | 17,169 | 2.16% | 32.8 | 3,616 | 0.56% |
| 22.3 | 27,848 | 3.52% | 32.9 | 7,010 | 1.07% |

Based on the results presented in Table 5.2.3, the cost of the $H_2$ fuel in order to have a viable business scenario is calculated to 22.1 and 32.7 €/kg$H_2$ for cases (a) and (b), respectively. Hence, by taking into account the statistical analysis of Table F3 in Appendix F, the cost per km for the FCEB refuelling process in SC5.2.1 equals to 0.0110 and 0.0098 €/km for cases (a) and (b), respectively. These results indicate that compared to the alternative city-oriented vehicles, the refuelling process cost of a FCEB in SC5.2.1 is 1.6 to 1.8 times higher than the BEB, while compared to the rest of the vehicles, it is found to be 2.8 to 7.8 times lower. The time required to refuel the FCEB in the HRS in both cases is the same as in SC5.2.2, and thus, it is significantly lower than the recharging time of the battery-powered counterparts but higher than that of the conventional counterparts.

The HRS sized for case (a), where hydrogen demand is higher, can be assumed to accommodate also the FCESs. By taking into account the calculated hydrogen price to have a feasible business case and the specification data for the FCES (Table F5), it can be derived that the cost per km of the FCES in this SC is 0.042 €/km, while the refuelling time is similar to the one in SC5.2.2. The refuelling cost is again higher than the light-duty battery based vehicles (i.e. BEB, BES) but lower than the BEV and the conventional vehicles. The refuelling time is similar to the recharging time of the battery-based vehicle counterparts.

### 5.2.4 Discussion

This study has addressed three RQs, aiming at finding the range of a FCEB under low-pressure hydrogen storage as well as the refuelling cost per km, and subsequently compare the respective refuelling/recharging costs of alternative urban suitable vehicles. The results of RQ1 showed differences in the range-to-energy consumption ratio in relation to the route followed and the case investigated (see Fig. 5.2.6). To examine the factors concerning the physical characteristics of the participants (e.g. age, weight, gender), a 'Spearman's rho' correlation was compiled to show if there are significant differences between the results of the FCEB range and the volunteer's characteristics (see Appendix F, Table F1). For case (a), the statistical analysis indicated no significant differences between the range of the FCEB and the physical characteristics of the participants (see Table G1 in Appendix G), while for case (b), the analysis showed a positive correlation of 0.878 between the gender and the range of the FCEB with a significance at the 0.05 level (see Table G2). What is also apparent is that the majority of the participants in case (a) were males, and thus, the results regarding the range-gender correlation cannot be considered adequately proven. In addition, it is obvious that the riding range results of the first four subjects in case (a) present significantly lower values than the riding range values of the remaining six participants (see Table F2). This is due to the lower current density of the on-board FC used to recharge the on-board battery pack (see Fig. 5.2.2) during the first hours of its lifetime resulting to lower efficiencies (Úbeda et al., 2012).

According to Fig. 5.2.6, the range-to-energy consumption ratios in case (a) are lower than in case (b). The reason is that during case (a), the battery pack of the FCEB system is fully charged through the operation of the on-board FC by supplying the necessary $H_2$ gas production during the refuelling process. Production and storage of hydrogen through electrolysis present efficiencies that range between 50% and 65% (Apostolou and Enevoldsen, 2019), and thus, although the available stored energy of the FCEB is higher (allowing a higher range) than case (b), the electrolysis efficiency is found to hinder the proportionally increase of the distance that the FCEB can cover. Therefore, based on the experimental data, it is more efficient (at least in terms of energy consumption) to operate the FCEB without initially recharging the battery through the operation of the FC.

As to RQ5.2.2, three scenarios were developed and assessed in order to appraise the refuelling cost of a FCEB compared to other vehicles suitable for urban transportation. The results derived in terms of the maximum refuelling cost per km and the refuelling time of the FCEB (case a) compared to the respective data of the vehicles' counterparts during the scenario analyses are presented in Fig. 5.2.8.

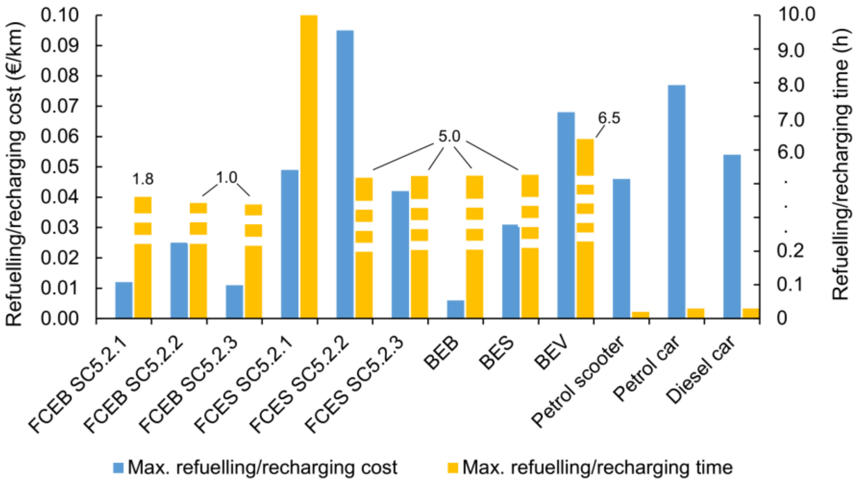



Fig. 5.2.8. Refuelling and recharging cost and time of urban private vehicles.

The depicted results in Fig. 5.2.8 show that the maximum values of refuelling cost of the FCEB are significantly lower than that of the conventional vehicles, lower than BES and BEV, and highly comparable to BEB primarily in terms of SC5.2.1. The refuelling time of FCEB in case (a) is much lower compared to battery-based vehicles, while compared to conventional vehicles only case (b) at SC5.2.2 and 3 is at the same order of magnitude (≈ 1-3 min). Nevertheless, it should be noted that the recharging process of a small battery electric vehicle such as the BEB and BES is currently much more accessible to the public compared to hydrogen-fuelled vehicles refuelling, which consists of a main barrier in the penetration of the later in the market. Additionally, the average energy consumption of the BEB could be lower than the one used for the calculations (i.e. 20 Wh/km) due to technology advances including higher charging efficiencies and larger battery capacities. In this regard, it is documented that contemporary BEBs might present energy consumption values down to 10 Wh/km (Frischknecht et al., 2016), which decrease the recharging cost of the BEB by half to 0.003 €/km enhancing the operating cost advantages of the BEB that stem from the hydrogen production-FC utilisation process efficiencies associated to the FCEB operation.

All the SCs for the FCES present a refuelling cost per km higher than the battery-based light duty vehicles and similar to the conventional scooter. However, it is important to mention that this result depends significantly on the scooter's efficiency and in the case of lower hydrogen consumption than the one used in this study (i.e. 1.9 $gH_2$/km) the results would present lower refuelling costs fully comparable with its battery-based counterparts. The refuelling time of the FCES is highly dependent on the specifications of the HRS in conjunction with the technology used for storing hydrogen on-board the vehicle. Metal hydride storage does not require the use of a compressor for storing the same hydrogen mass in gas canisters resulting to lower fuel cost. However, in order to achieve similar refuelling times of metal hydride canisters to a high-flow compressed $H_2$ gas storage process, a cooling system is required to be implemented in the respective HRS increasing the capital and operational expenses of the HRS and thus the final hydrogen cost.

The summarised results of the three investigated scenarios for the FCEB are presented in Fig. 5.2.9 below. The results clearly show an advantage of SC5.2.1 for case (a), while for case (b), although the cost-to-range ratio in SC5.2.1 is slightly lower compared to SC5.2.1, the refuelling time of the latter is substantially more advantageous. Comparing the two cases for SC5.2.1 to answer RQ1, case (b) seems to be less costly and timesaving than case (a) due to the lower efficiency of the recharging phase of the on-board battery in case (a) and the higher hydrogen refuelling flow rate respectively.

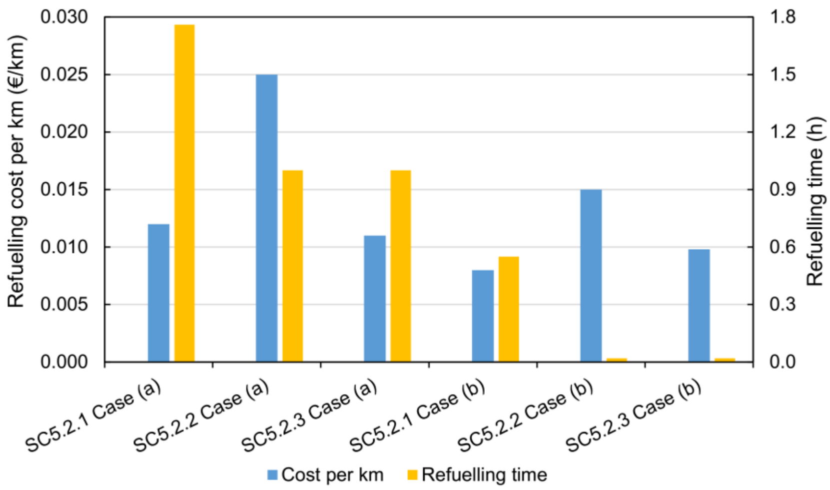



Fig. 5.2.9. Results of the cost-to-range ratio and refuelling time for all investigated scenarios in both refuelling process cases of the FCEB.

The participants' opinion (RQ5.2.3) about the FCEB operation was positive in both investigated cases, and more than 70% replied that they would consider using a FCEB as their daily means of urban transportation with a refuelling price of 1.339 €. By taking into consideration the data regarding the FCEB lowest range for both cases found in Table F2 in Appendix F, the refuelling cost per km that the participants are willing to pay ranges between 0.036 (case b) and 0.103 €/km (case a). Based on the values found during the investigated scenarios for both cases (a) and (b) (see Fig. 5.2.9), the price the participants are willing to pay has been found to be much higher. The participants' answers regarding willingness to pay are comparable to the cost ratios of conventional vehicles, and thus, the perspective of using a more economical transportation such as the use of a FCEB would positively affect the transition to 'greener' urban mobility vehicles.

However, it is worth noting that this study did not take into consideration the capital and maintenance costs of the FCEB and what would be the impact to the participants' opinion. Currently, the capital cost of the FCEB can be quoted at least twice more expensive compared to an average cost of a BEB due to the FC related components price, while maintenance costs of a FCEB/FCES might present higher values compared to a BEB/BES because of the system's complexity or FC degradation over time. Hence, further comparison between the two technologies would provide interesting data in regards to the FCEB/FCES prospects in the respective market.

Based on the previous analyses and the derived results, the contribution of this paper in the existing knowledge can be described by the following four statements:

The hydrogen fuel cost as calculated based on the HRS specifications, the driving SCs and the efficiency of light-duty FCEVs plays a significant role on the penetration of this technology in the alternative vehicle market for urban mobility.

- The battery recharging process via the FC affects significantly the refuelling cost of light vehicles that use the FC as a driving range extender.
- The best refuelling cost SC for a FCEB is achieved in SC5.2.1 were a small hydrogen generator is used. SC5.2.1 on the other hand, consisting of an on-site grid connected HRS provided slightly higher refuelling cost but significantly lower refuelling time.
- Refuelling times of light-duty FCEVs are highly dependent on the storage technology used. Metal hydrides seem more appropriate for smaller hydrogen storage capacities.

### 5.2.5 Conclusions

This research has focused on the investigation of a light-duty fuel cell vehicle suitable for urban transportation such as a hydrogen-powered bicycle (i.e. a FCEB). The operational characteristics of the FCEB in terms of driving range, range-to-energy consumption and refuelling cost per kilometre were assessed by means of an experimental methodology consisting of FCEB refuelling and riding processes under low-hydrogen storage pressure. The applied methodology examined two cases in relation to the initial SOC of the vehicle's on-board battery pack as well as three different refuelling scenarios concerning the hydrogen fuel cost.

Sixteen volunteers participated in the experiment, who were subsequently asked to answer a questionnaire, stating their opinion of the FCEB. The derived results indicated that the range-to-energy consumption ratio of the FCEB depends mostly on the route followed and the process followed to charge the on-board battery pack of the vehicle. The physical characteristics and specifically the gender of the participants proved to play a significant role in the case where the battery of the vehicle initially was discharged and only the hydrogen canister was filled with $H_2$ fuel. However, as discussed, the low number of participants during the experiment did not provide accurate results in terms of the correlation between the energy consumption and the driving range of the FCEB, and thus, further investigation of these parameters with more participants might derive different and/or more robust results.

The driving range-to-energy consumption ratio of the FCEB under low-pressure hydrogen storage was found to be between 20 and 46 km/kWh depending on the routes, the participants' riding pattern and the cases investigated (a or b). The median values for case (a) were estimated to 36.6 and 20.5 km/kWh for the lower (Route 1) and higher slope (Route 2) routes, respectively, while for case (b), the respective values were calculated to 43.3 and 34.2 km/kWh. This indicates that the slope of the route plays a significant role in the autonomy of a FCEB, while the recharging of the on-board battery pack through the FC (case a) presents lower efficiencies that negatively affects the driving range of the vehicle.

Based on the results of this study, it is clear that the prospects of FCEBs and FCESs as urban transportation means present several advantages but also drawbacks over their counterparts. Refuelling cost per km of the FCEBs seems to be significantly lower than conventional and larger battery-based vehicles but higher than a BEB. On the other hand, the refuelling cost per km of the FCESs is higher than the smaller battery-based vehicles but lower than the conventional vehicles. To this end, additional research is required on less costly refuelling options such as off-site HRSs, HRSs able to support metal hydride storage or HRSs powered by excess RES energy that otherwise would be lost. Research on the operation of a FCEB under a medium/higher $H_2$ storage pressure or other storage technologies (e.g. metal hydrides) is also necessary in order to provide a detailed assessment of the refuelling costs and the range-to-energy consumption ratio.

## 5.3 Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market

Road transportation consists of a significant contributor to total greenhouse gas emissions in developed countries. New alternative technologies in the transportation sector such as electric vehicles aim to reduce substantially vehicle emissions, particularly in urban areas. Incentives of using two-wheel electric vehicles such as bicycles in big cities centres are promoted by local governments, and in fact, some countries are already trying to adopt this transition. An interesting case consists of the use of hydrogen fuel cells in such vehicles to increase their driving range under short refuelling times. To this end, this paper investigated the social and financial prospects of hydrogen infrastructure for city-oriented fuel cell electric vehicles such as bicycles. The results of the research indicated that a light mobility urban hydrogen refuelling station able to provide refuelling processes at pressures of 30 bar with a hydrogen fuel cost of 34.7 €/kg$H_2$ is more favourable compared to larger stations.

### 5.3.1 Introduction

During the last two decades $CO_2$ emissions, which comprise the highest share to global GHG emissions exceeding 65% of total GHGs increased from 23.2 Gt in 2000 to 32.8 Gt in 2017 respectively, from which 5.9 Gt were emitted from road transportation (passenger and freight vehicles) (IEA, 2020a, 2020b). In the last two decades, $CO_2$ emissions from passenger vehicles increased by approximately 43% presenting a continuously growing trend reaching in 2018 3.6 Gt (IEA, 2020a).

In this context, transportation in urban environments is one of the major contributors of $CO_2$ emissions due to overpopulation, which is expected to consist 80% of the entire population by 2030 resulting to more vehicles, traffic, and higher travelling mileage (Grote et al., 2016; Yuan et al., 2019). In countries such as China where high development rates are observed, this phenomenon is intense. In Beijing only, 17 Mt of $CO_2$ emissions in 2014 came from passenger vehicles, while the respective emissions in other 6 major cities reached in total approximately 35 Mt (Yuan et al., 2019). In the EU, 40% of road transportation induced $CO_2$ emissions is estimated to come from urban transport accounting in 2017 354 Mt, and consisting of 10.4% of total $CO_2$ emissions (EU, 2018; European Commission, 2020b). To this end, many city authorities in EU incorporated or planned measures to reduce as much as possible road transportation emissions. Among those, promotion of cycling and use of public transport, use of EVs (including cars, buses and bikes) and vehicle sharing programmes are plans adopted by metropolitan areas including Berlin, Paris, Vienna and Prague (Doğan Öztürk et al., 2019). Additionally, other countries nowadays provide incentives to support 'green' mobility in urban areas focussing on the promotion of AFVs. The state of California aims to reduce $CO_2$ emissions by overseeing several incentive programmes designed to increase the sales of light-duty AFVs such as BEVs and FCEVs and develop the required recharging/refuelling infrastructure (Brown et al., 2018). The promotion of EVs by the Chinese government through the new energy vehicles programme focussing on the R&D of EVs, resulted to a significant increase of the number of electric passenger vehicles reaching 370,000 and 250 million electric buses and two-wheel vehicles respectively (Coalition for Urban Transitions, 2019).

Acknowledging the above, the evolution of EVs seems to be one of the major assets towards the mitigation of transportation induced GHG emissions (IEA, 2020a). Light-duty EVs for city transportation such as bicycles or scooters are described as an alternative to larger conventional vehicles towards the reduction of carbon emissions in city centres (Apostolou, 2020b). During the last 20 years, several studies investigated the prospects of small hydrogen-based vehicles (e.g. FCEBs, FCESs) in urban transportation. Some of these focussed more on the technical aspects of this vehicle technology including the efficiency and the overall performance of pilot projects under real conditions or through modelling and simulation of the vehicles' operation and refuelling options (Apostolou et al., 2019; Cardinali et al., 2002; Chao et al., 2009; Hu et al., 2020; Hwang et al., 2004; Kheirandish et al., 2014; Tso et al., 2012). Most of these research articles presented positive results for the light hydrogen vehicles compared to alternative vehicle counterparts and conventional mobility, while the most identified drawback consisted the lack of refuelling infrastructure and the high operating costs due to the increased respective hydrogen fuel price. On the other hand, the benefits of such vehicles in terms of social and environmental aspects were also examined in the international literature showing a clear advantage over the urban conventional vehicles. A predominance over other alternative vehicles which is however highly affected from the energy mix used to provide the respective energy input to the under comparison vehicles is also documented by a series of studies (Bicer and Dincer, 2017; Hwang, 2012; Li et al., 2016; Mellino et al., 2017; Tso and Chang, 2003; Uyar et al., 2019).

As it was previously mentioned, the acceptance by the public and therefore the further expansion of this vehicle market is highly dependent on the respective refuelling infrastructure and the associated costs. This research consists of the continuation of a study published by Apostolou (2020b) concerning the refuelling cost scenarios of a FCEB under low-pressure hydrogen storage of 30 bar (Apostolou, 2020b). The aim of this paper is, on the one hand, to investigate the refuelling costs of a FCEB under real-world conditions and higher hydrogen pressures, and on the other, to assess the opinion of potential future adopters concerning the different refuelling options of a FCEB and their respective costs. In this regard, this study provides the best economic scenario in terms of hydrogen infrastructure implementation for light-duty fuel cell vehicles with hydrogen gas storage.

### 5.3.2 Methodology

The methodology followed during this research is divided in three main parts consisting of an experimental phase, a financial analysis, and a survey. The experimental phase of this research included the refuelling processes of the same FCEB as the one used in (Apostolou, 2020b) under hydrogen pressures of 30, 100, 150, and 200 bar. The refuelling processes were performed in an autonomous on-site HRS powered by a PV park of 62 kW peak power located in the 'Aragon Hydrogen Foundation' research centre in Spain. The hydrogen generator consisted of a 50 kW PEM electrolyser including the BOP components and the compression system, which comprised a 350 bar outlet pressure (suction pressure up to 20 bar) two-stage diaphragm hydrogen compressor of 4.8 kW rated power and a maximum hydrogen outlet flow of 11.2 $Nm^3/h$.

Following the refuelling processes, the autonomy of the FCEB was estimated by selecting a route in the city of Huesca, Spain (Fig. H1, Appendix H), similar to the routes followed during the experimental phase of (Apostolou, 2020b). For validating the driving range results compared to those of (Apostolou, 2020b), a refuelling process followed by the estimation of the autonomy under hydrogen storage at 30 bar was performed for the specific route. The number of positive slopes was also recorded (Fig. H2, Appendix H) indicating similar characteristics to route two used in (Apostolou, 2020b). During the experimental phase, the weather conditions were selected to be similar for all the riding procedures under the different refuelling pressures. The riding average speed in all cases remained similar, while all processes were held by the same individual and performed twice to get a confirmation of the results.

The initial SOC of the FCEB's buffer battery prior to each experimental part was 100%. The reason for choosing a fully charged battery was to find the highest possible driving range that can be achieved by the same rider under the different investigated refuelling pressures. Based on the above the total hydrogen consumption included also the recharging of the FCEB's battery pack through the on-board FC.

The financial analysis was based on real data acquired during the refuelling processes of the FCEB concerning the operating costs for producing one kg of hydrogen. However, due to the different investigated pressures, the compressor's specifications and thus the respective capital and O&M costs were used only for the higher pressure (i.e. 200 bar); while for the lower pressures, smaller compressors were taken into consideration. In order to calculate the hydrogen fuel cost for each investigated refuelling pressure and compare it with the results of (Apostolou, 2020b), the NPV of an on-site HRS investment in Denmark was calculated from Eqs. 4.2.37 and 4.2.38. According to (Apostolou, 2020b), three investigated scenarios concerning the refuelling processes of a FCEB indicated that the lowest refuelling price offered by an on-site HRS could be achieved from a grid-connected topology. Hence, this research focussed entirely on this type of HRS in order to find the optimum fuel cost case for a consumer. The minimum hydrogen fuel cost for all refuelling cases was calculated with respect to getting a positive NPV and a PP of approximately 10 years.

The proposed HRS is presented in Fig. 5.3.1, while the specifications of the station's main components are included in Table 5.3.1. The hydrogen production and storage data were based on the topology used during the experimental phase. For the process of hydrogen compression, three commercial compressors (100, 200 and 350 bar) were assessed to be the most appropriate for the refuelling processes at pressures of 30 (by the 100 bar compressor), 100 (by the 200 bar compressor), 150 (by the 200 bar compressor) and 200 bar (by the 350 bar compressor).

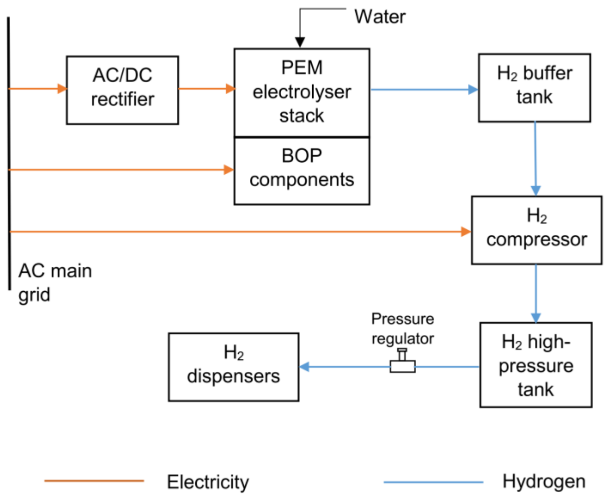



Fig. 5.3.1. Proposed on-site HRS for light-duty vehicles.

According to Ulleberg and Hancke (2020), the max capital cost of a compressor with low outlet $H_2$ flow (< 20 $Nm^3/h$), low suction pressure and a pressure discharge between 200 and 300 bar is approximately €77,700 (Ulleberg and Hancke, 2020). To this end, it can be assumed that the specific cost of a compression unit of similar specifications that has an approximate rated power of 4 kW is on average 19,400 €/kW (see Table E1, Appendix E). The dispenser capital cost was based on the fact that a hydrogen dispenser of 350 bar with low hydrogen flow rate (≤ 20 $Nm^3/min$) does not require a cooling circuit (Ulleberg and Hancke, 2020) and thus it can be assumed to have a cost similar to a contemporary compressed natural gas dispenser (Parks, 2014). Based on the maximum outlet hydrogen flow of the electrolyser and the operating hours of the station, the daily hydrogen production ($M_{H2}$) can be estimated to 16.6 $kgH_2$.

Table 5.3.1. Specifications of the HRS components.

| Parameter | Power (kW) | Max. outlet $H_2$ flow rate ($Nm^3/h$) | Mass capacity ($kgH_2$) |
|---|---|---|---|
| PEM electrolyser | 50 | 14.2 | - |
| 100 bar $H_2$ compressor (Hydro-Pac inc., 2020) | 2.3 | 17.4 | |
| 200 bar $H_2$ compressor (Hydro-Pac inc., 2020) | 3.8 | 16.9 | - |
| 350 bar $H_2$ compressor | 4.8 | 11.2 | - |
| $H_2$ buffer tank capacity at 20 bar | - | - | 7 |
| $H_2$ high pressure tank capacity at 350 bar | - | - | 23 |

The investment cost of the HRS is calculated by Eqs. 5.3.1 and 5.3.2.

During the operation of the small-scale one-dispenser HRS two employees are assumed to work on shifts, while the footprint of the station able to accommodate all components is assumed to be 300 $m^2$. Eq. 5.3.3 is used to calculate the daily FCEBs refuelling processes that the proposed HRS can accommodate in a daily basis (operating hours assumed between 8:00 AM to 9:00 PM similarly to Apostolou (2020b)). The lifetime of the project ($n$) was set to 20 years, resulting in approximately 95,000 operating hours. According to (Perez and Casero, 2019), the PEM electrolyser used for this research has a lifetime of 80,000 h, suggesting that the electrolyser's stack is required to be replaced during the project's lifetime. The loan to total capital investment ratio was assumed to be 0.5, while the loan re-payment time was set to 10 years.

$$IC_o = IC_{el}\, P_{max} + IC_{comp}\, P_{comp} + IC_{bfr}\, M_{H2bfr} + IC_{H2stor}\, M_{H2hp} + IC_d + IC_{constr}, \tag{5.3.1}$$

$$IC_{constr} = (IC_{el}\, P_{max} + IC_{comp}\, P_{comp} + IC_{bfr}\, M_{H2bfr} + IC_{H2stor}\, M_{H2hp} + IC_d) * (f_{cost,constr} + f_{cost,\, cont}), \tag{5.3.2}$$

$$N_{bikes} = M_{H2} / m_{H2,cons}, \tag{5.3.3}$$

The calculation of the annual O&M costs (see Table E1, Appendix E) was taken as a percentage of the investment cost plus the stack replacement cost after 10th operating year ($FC_{el}$) for the maintenance part, while the operating part was estimated by Eq. 5.3.4 describing the annual energy consumption of the system.

$$E_{cons} = 365 * M_{H2} * (Ec_{electr} + Ec_{comp}), \tag{5.3.4}$$

The data used for the calculation of the parameters of Eqs. 5.3.1 to 5.3.4 are presented in Table E1 (Appendix E).

Following the financial analysis, the results were disseminated through the simulation of an HRS operation during a workshop-based lecture to 17 students of Aarhus University, Denmark who declared using regularly a bicycle/scooter for their daily commutes. The students thereafter participated in an anonymous survey via the '*SurveyXact*' software and asked to state which of the different hydrogen fuel costs calculated for the different refuelling pressures and the respective autonomy of a FCEB believed that was more appealing to them. The survey results were then categorised to identify which of the refuelling processes under different pressures and therefore which HRS specifications would be more favourable in a future urban hydrogen market.

### 5.3.3 Results and discussion

The experimental phase of this research included the refuelling process of the FCEB under different hydrogen pressures and subsequently the estimation of the vehicle's autonomy (full depletion and discharge of the hydrogen tank and battery pack respectively). The financial evaluation calculated the $H_2$ fuel price were the NPV becomes positive for the respective HRSs. For the case of an HRS suitable for the 30 bar refuelling process, the results indicated a minimum hydrogen price of 34.7 €/kg$H_2$ to get a positive NPV. Similarly, for the 100, 150 and 200 bar, the $H_2$ price accounted for 36.0, 36.1, and 36.9 €/kg$H_2$ respectively. The results of the riding phase calculated by the means of the two riding procedures for all refuelling pressures and the hydrogen price per km are presented in Table 5.3.2.

Table 5.3.2. Hydrogen consumption, autonomy and average speed during the experimental phase.

| **Parameter** | **Refuelling hydrogen pressure (bar)** | | | |
|---|---|---|---|---|
| | 30 | 100 | 150 | 200 |
| $m_{H2,cons}^{*}$ ($gH_2$) | 15.1 | 24.8 | 32.8 | 38.8 |
| $N_{bikes}$ | 1,099 | 669 | 506 | 427 |
| Autonomy (km) | 27.8 | 43.9 | 59.2 | 72.8 |
| Average speed (km/h) | 20.1 | 20.6 | 21.3 | 22.3 |
| Total refuelling cost (€) | 0.52 | 0.89 | 1.18 | 1.43 |
| HRS $IC_o$ (€) | 291,770 | 327,560 | 327,560 | 351,420 |
| Minimum $H_2$ price for positive NPV (€/km) | 0.019 | 0.020 | 0.020 | 0.019 |

* Hydrogen consumption includes the hydrogen mass stored inside the on-board FCEB's tank and the hydrogen consumed to fully-charge the battery pack of the FCEB.

Table 5.3.1 results demonstrate an almost similar cost per km for all the investigated refuelling pressures. This suggests that the hydrogen fuel cost increase due to the different HRS specifications to accommodate the different refuelling pressures is counterbalanced with the FCEB's autonomy increase as refuelling pressure gets higher. It is also apparent that the fuel cost for the 100 and 150 bar refuelling pressure is approximately the same (small deviation due to different O&M costs), which clearly gives an advantage towards the latter refuelling pressure option. By comparing the cost per km results for the

FCEB with the respective results from (Apostolou, 2020b) (i.e. SC5.2.1, first investigated case) one may argue that there is a deviation between the final values (0.011 and 0.019 €/km). Although the $IC_o$ in both studies is approximately the same, the cost data used in this research corresponds to an operating HRS able to provide a specific daily amount of $H_2$ fuel while the results from (Apostolou, 2020b) were based on theoretical scenarios. These scenarios considered higher hydrogen fuel demands, which could offer substantially more revenues to an investor, allowing thus lower hydrogen fuel prices to get the lowest positive NPV in the business case study.

By taking into account the results documented in Table 5.3.1, the survey respondents indicated that the refuelling process under 30 bar of pressure was more financially appealing in accordance with their daily commuting needs. Specifically, most of the participants (41.2%) declared a daily travelling routine between three and five kilometres in an urban environment. Approximately half of the survey respondents (47.1%) favoured the low-pressure refuelling because of the lower total cost (see Fig. 5.3.2).

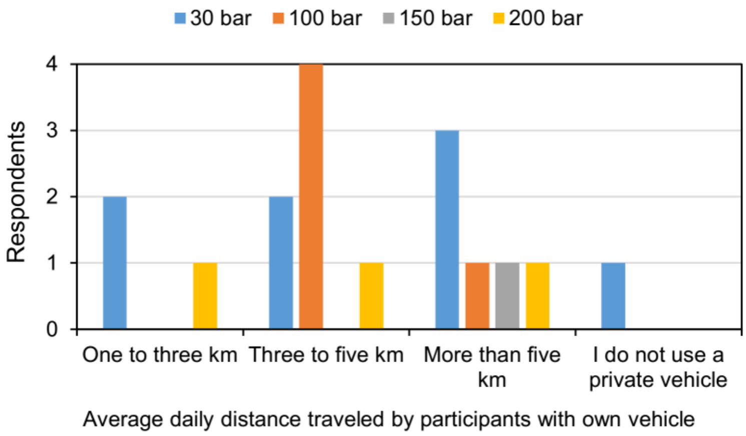



Fig. 5.3.2. Responses received by the workshop's survey participants.

The 30 bar refuelling option dominated among the workshop's participants who declared an average daily commuting trip less than three and more than five km. On the other hand, the respondents answered three to five km of average commuting trips favoured clearly the 100 bar refuelling option leaving as a second option the lower pressure of 30 bar.

Based on the survey's result, it seems that urban commuters travelling short distances in their daily routine take the total refuelling cost more into account compared to the fuel cost per kilometre, which in the case of the FCEB is almost similar for all cases. To this end, the low refuelling pressure option of 30 bar and the medium pressure of 100 bar are the prevalent ones suggesting a lower cost investment for an HRS able to accommodate small urban hydrogen vehicles. By taking all the above into account, the novelty of this study can be quoted in three aspects:

- Identification of the best refuelling scenario for light urban hydrogen vehicles.
- Proved independency of the hydrogen price per km for refuelling at different hydrogen pressures. Valid for the same rider for the same route.
- Small-scale hydrogen refuelling stations for small urban hydrogen vehicles are favoured compared to larger stations (for both investors and consumers).

### 5.3.4 Conclusions

This research presented an investigation of hydrogen gas refuelling processes of a small urban vehicle such as a FCEB. Different refuelling pressures were studied in order to assess the operation of the vehicle and the financial factors in regards to the respective hydrogen refuelling infrastructure. The data were based on the operation of an on-site HRS and used to estimate the best refuelling scenario for a FCEB in terms of the hydrogen fuel price. Although the results showed an increasing hydrogen fuel cost between 34.7 and 36.9 €/kg$H_2$, the fuel cost per km remained fixed at approximately 0.019 €/km. However, it should be noted, that although the HRS investment costs can be considered to be similar between different countries, the operating costs, which are highly dependent on the electricity costs and financial parameters (e.g. taxation schemes, interests, etc.) would differ between countries and hence would affect the final hydrogen fuel cost. What is apparently interesting is that based on this study results, the fuel cost per km for the same rider following the same route was found to remain constant and independent on the refuelling pressure of the FCEB.

The outcome for all investigated hydrogen refuelling pressures was disseminated to a workshop's participants where a FCEB and the proposed HRSs were presented. The participants were asked to document their preference on the hydrogen fuel cost results for the refuelling pressures and the respective delivered FCEB autonomy based on their average daily urban commuting needs. The responses showed that the participants favour more the lower pressure refuelling process compared to high-pressure options for their daily commutes.

## 5.4 Refuelling scenarios of a light urban fuel cell vehicle with metal hydride hydrogen storage. Comparison with compressed hydrogen storage counterpart

The high price of hydrogen fuel in the fuel cell vehicle refuelling market is highly dependent on the one hand from the production costs of hydrogen and on the other from the capital cost of a hydrogen refuelling station's components to support a safe and adequate refuelling process of contemporary fuel cell vehicles. The hydrogen storage technology dominated in the vehicle sector is currently based on high-pressure compressed hydrogen tanks to improve as much as possible the driving range of the vehicles. This technology however mandates the use of large hydrogen compression and cooling systems as part of the refuelling infrastructure that consequently increase the final cost of the fuel. This study investigated the prospects of lowering the refuelling cost of small urban hydrogen vehicles through the utilisation of metal hydride hydrogen storage. The results showed that for low compression hydrogen storage, metal hydride storage is in favour in terms of the dispensed hydrogen fuel price, while its weight is highly comparable to the one of a compressed hydrogen tank. The final refuelling cost from the consumer's perspective however was found to be higher than the compressed gas due to the increased hydrogen quantity required to be stored in MH tanks to meet the same demand.

### 5.4.1 Introduction

During the last decade there was a significant increase of EVs due to the continuously support of governments and stakeholders towards a carbon free transportation sector, which is responsible for the 26% of global $CO_2$ emissions in 2018 (IEA, 2020c). The transportation sector induced GHG emissions in EU-28 increased from 0.79 Gt $CO_2$-eq in 1990 to 0.95 Gt $CO_2$-eq in 2017 from which 95% is caused from road transportation (Eurostat, 2020a). The targets set by the EU-28 to mitigate the road transportation induced $CO_2$ emissions (≈ 20% of total emissions) aim at a 23% reduction of GHG emissions from road transportation by 2030, while specific emission targets were applied to manufacturers to reduce the vehicles' emissions by 37.5% from 2030 onward. Specifically, for low/zero emission vehicles, the manufactures' targets would be relaxed in case of introducing 35% annual share of this type of vehicles in their fleet (Cabuzel, 2020).

In EU-28, more than 1.35 million EVs are currently on the roads compared to 5,613 units in 2010 (EAFO, 2020) suggesting a rapid integration of the new vehicle technology in the transportation market. However, the share of EVs in the total number of vehicles in EU-28 is still very low accounting of 0.56% indicating that EV market is still at an early stage of development. EVs include three main vehicle technologies: The BEVs, PHEVs and FCEVs (McKinsey & Co, 2010). Among those three vehicles types, PHEVs are low emission, while BEVs and FCEVs are considered zero direct emission vehicles.

BEVs compared to FCEVs present advantages and drawbacks that are based on the inherent characteristics of each technology.

Although both technologies are environmentally friendlier than conventional vehicles, they exhibit a carbon footprint in an LCA (Cox et al., 2020). According to (Bicer and Dincer, 2017), FCEVs present a lower warming potential compared to BEVs, while Shin et al. (2019) concluded that FCEVs less carbon intensive in an LCA compared to BEV in the case of getting the hydrogen fuel as an industrial by-product. In this context, Thomas (2009) suggested that FCEVs are environmentally friendlier than BEVs in an LCA only if the electricity mix of a country is fossil fuel based. In support to the above, Cox et al. (2020) suggests that FCEVs present better environmental performance than BEVs only in the case of having higher carbon intensity of the electricity mix than the one of a combined cycle natural gas powerplant (Cox et al., 2020). Similarly, Li et al. (2016) stated that between BEVs and FCEVs, the vehicles presenting the best environmental footprint depend on the energy mix and the methods of producing the hydrogen fuel (Li et al., 2016).

BEVs compared to FCEVs are considered more urban oriented vehicles due to their lower mileage autonomy and better efficiency. To this end, the energy consumption per 100 km of a contemporary BEV is almost 50% less than a FCEV (Velazquez Abad, 2017). Additionally, the recharging cost of a BEV may be considerably lower (depending on the electricity costs) than the unsubsidised refuelling cost of a FCEV which is currently in the same level for most countries. In this context the total ownership cost of the BEVs is currently lower than that of the FCEV with however a declining trend of the price of the latter that is expected to converge in the future towards the price of the rest EVs (McKinsey & Co, 2010; Morrison et al., 2018; Thomas, 2009; Velazquez Abad, 2017). One may also argue that recharging a BEV might be more convenient as it can occur apart by using a fast charger in the premises of each owner, while the refuelling process of a FCEV occurs only through an HRS. HRSs are still not available everywhere with their total number not exceeding 470 station at the end of 2019 contributing to the low number of FCEVs on the roads and vice versa (i.e. 25,210 vehicles at the end 2019) (IEA, 2019c). On the other hand, FCEVs present advantages over the BEVs including higher autonomy and fast refuelling times that are comparable to that of conventional vehicles. A contemporary passenger FCEV may reach a driving autonomy of approximately 650 km, while its refuelling time does not overpass 3 min (Brey et al., 2018; Kurtz et al., 2019). Based on the above, it can be derived that the most significant drawbacks of the FCEVs are the refuelling costs and the accessibility of the appropriate refuelling infrastructure.

The high refuelling cost of FCEVs can be identified as the results of the hydrogen fuel production process cost and the high capital cost of the key components of a HRS (Apostolou, 2020a). According to Apostolou and Xydis (2019) there are two main categories of HRSs, the on-site and the off-site hydrogen production stations (Apostolou and Xydis, 2019). Both types of stations include the same systems except the hydrogen source availability and its respective equipment. Hydrogen is produced via a water electrolysis system or a steam methane reformer in an on-site HRS, while in an off-site, hydrogen fuel is delivered via trucks from a centralised production facility. Due to the inherent properties of hydrogen, the refuelling of the gas hydrogen is occurring under high pressures (i.e. 350 or 700 bar) in both types of HRSs to be able to store an adequate mass of hydrogen in a confined space of a vehicle's tank. To this end, HRSs main components include a large hydrogen compressor to raise the hydrogen pressure and in case of high refuelling flow rates a cooling system for lowering the fuel temperature before the refuelling process at –40 $^{o}$C and avoid the tank's temperature exceeding 85 $^{o}$C as set by the tank manufacturers (Apostolou and Xydis, 2019). The cost of these systems depends on the size of the HRS and may range between €324,000 and €480,000 for the compressor unit and €162,000 and €200,000 for the cooling system (Apostolou and Xydis, 2019).

This established method of storing hydrogen as a pressurised gas in passenger FCEVs mandates the use of the above-mentioned components and a further fuel cost reduction based on the specific equipment cost decrease would proceed through economies of scale. However, in light urban vehicles market including FCESs or FCEBs, these HRS key components could be bypassed through the utilisation of a different on-board hydrogen storage method. Among several methods of storing hydrogen the most popular apart from the compressed gas storage are the liquid storage inside special cryogenic tanks and storage in MH canisters (Kavadias et al., 2018). Liquid storage is inherently energy intensive and unsuitable for the transportation sector due to the required equipment for storage under cryogenic temperatures. In contrast, MH storage is based on the ability of intermetallic components to reversibly absorb hydrogen at low operating pressures depending on the material used (Kavadias et al., 2018). MH storage presents also very high storage capacity of hydrogen per unit volume, high safety, and provides high purity hydrogen stored quantity (Davids et al., 2019). The main drawback of MH storage is documented to be the low storage density by weight, resulting to high weight of the canister in order to secure adequate hydrogen quantities to provide fuel to transport applications (Lototskyy et al., 2020). However, in the case of FC light vehicles such as carts, scooters, and bicycles, where hydrogen fuel demand is significantly lower compared to larger vehicles, the utilisation of MH storage technology could provide several benefits (Davids et al., 2019).

Amica et al. (2020) compared the costs of hydrogen gas storage under 700 bar pressure with the costs of storing in MHs for road FC vehicle applications normalised by $kgH_2$. The outcome showed that even with a high deployment of MHs, the cost ratio is currently at least 2:1 in favour of compressed gas storage. The authors however stated that the maturity of the MH technology could counterbalance the cost difference in the future (Amica et al., 2020). In the same context, Frank et al. (2019) investigated how the refuelling costs of FCEVs could minimise in case of using MH hydrogen storage instead of high compressed storage on-board the vehicles. The maximum savings were found to be 0.63 €/kg$H_2$ mostly due to the reduction of the compression costs (Frank et al., 2019).

Sizing of a MH storage system was modelled by Brooks et al. (2020) providing estimation about the mass, volume, and overall dimensions of the system to be able to supply 5.6 kg$H_2$ to a vehicle. The results of the model showed that the physical properties of the MH tank material play significant role during the sizing of such systems able to follow the technical targets set by US Department of Energy (Brooks et al., 2020). Mazzuco et al. (2014) argued that in order be consistent with the Department of Energy requirements in terms of charging time `and volumetric density of light-duty FCEVs MHs, design and heat management of the tank is crucial. The authors documented that cooling and heating of the MH system during the absorption and desorption processes respectively improve the storage capacity and refuelling times (Mazzucco et al., 2014). The thermal properties of MH storage and how could be utilised in BEVs with FC range extenders have been investigated by Nasri and Dickinson (2014). The authors developed a thermal management system with a thermally coupled high temperature PEM FC and a MH tank where heat absorption during the hydrogen release of the MH storage cooled down the FC during the operation of the latter. Additionally, they noted that the volume of the MH tank plays an important role on the operating time of the extender due to the thermal connection of the FC and the thermal behaviour of the tank during the operation of the system (Nasri and Dickinson, 2014). Kölbig et al. (2019) presented results about the characteristics of MH hydrogen storage for sub-zero temperatures, which are highly important for FCEVs operation in winter conditions by providing heat to the FC during cold starts. The authors studied two materials consisting of $LaNi_{4.85}Al_{0.15}$ as heat generating material and $Ti_{0.95}Zr_{0.05}Mn_{1.46}V_{0.45}Fe_{0.09}$ as hydrogen supply material. The results showed that for an adequate pre-heating, it is required to use increased mass of the materials that consequently could lead to hydrogen gas and heat transport limitations (Kölbig et al., 2019).

Lototskyy et al. (2015), studied the desorption behaviour of various MH types applicable for stationary and mobile low temperature PEM FCs. The results indicated that hydrogen supply to the FC was decreased due to the endothermic hydrogen desorption that depends on the size of the MH canister, the heat management conditions of the MH, and the layout of the MH tank in relation to the heat transfer intensification in the intermetallic material (Lototskyy et al., 2015). Similarly, Han et al. (2020) investigated two types of MH (AB5 and AB2) and their physical properties to assess which was the most appropriate for mobile applications. The authors concluded that the $AB_5$ type performed better in charging times but compared to $AB_2$ lacked storage capacity by 18.3%. Furthermore, the $AB_2$ type presented also higher desorption pressure making it more appealing for use at colder climates (Han et al., 2020). The alternative of refilling MH hydrogen tanks of FCEVs off-board the vehicles was examined by Lieutenant and Borissova (2020). Although their research showed many benefits compared to on-board storage, the selection of the proper storage material was proved to be significant. Off-board refilling of MH tanks would allow higher pressure and temperature processes reducing thus the required storage material and minimising the refilling times. The exothermic MH storage reaction release heat which could be also used for heating the spaces of the HRS (Lieutenant and Borissova, 2020).

The use of MH hydrogen storage in light-duty FCEVs was studied by Hwang and Jiang (2012) who developed and tested a small hybrid FC-battery vehicle. The maximum efficiency of the system was estimated to 46% on one hand due to the FC stack operation and on the other due to the utilisation of the produced heat by the FC to the MH tank for the desorption of hydrogen fuel (Hwang and Chang, 2012). Lototskyy et al. (2020) documented the benefits in terms of compactness with low increase of weight and higher safety through the implementation of MH storage in FC forklifts. Although the prototype power module combined with the MH storage presented higher refuelling times and insignificant weight increase, low pressure during operation and refuelling processes suggested increased safety and lower refuelling costs respectively (Lototskyy et al., 2020). The refuelling process of an electric forklift powered by a FC was investigated by Lototskyy et al. (2016). The hydrogen storage system comprised a compressed gas and MH hydrogen tanks, while the HRS used also a MH compressor for delivering hydrogen to dispensers under 200 bar of pressure. The documented by the authors benefits of using lower refuelling pressure compared to the ones required for compressed gas on-board storage included use of standard auxiliary components (e.g. valves, fittings, etc.), no overheating of the hydrogen fuel eliminating the requirement of cooling the fuel prior the filling process, and the use of a MH compressor reducing the electricity consumption of a mechanical compressor (Lototskyy et al., 2016a).

Tso et al. (2012) presented the results of a FCES project in Taiwan including real data statistics and analysis of 27 FCESs with MH hydrogen storage of 90-100 $gH_2$ under real operating conditions. The outcome of their study revealed that ambient temperatures <15 $^oC$ affected the operation of the MH storage, especially during start-up times (Tso et al., 2012). The hydrogen discharge rate was found to be less than 40 $gH_2$ when flow rate was more than 12 SL/min resulting to additional heat requirement for the hydrogen release reaction to occur (Hwang, 2012). Additionally, the hydrogen to metal ratio of the MH canisters was calculated between 1.03% and 1.10% suggesting that storage effectiveness needs to be better in order to improve the overall weight of the vehicles (Tso et al., 2012). The operation of a FCES with $AB_2$ type MH storage was assessed by Davids et al. (2019). The thermal management of the MH storage occurred through air convection using ambient air with temperature between 15 and 25 $^oC$. The hydrogen capacity was of the storage vessel was estimated to approximately 80 $gH_2$, which were not fully utilised due to the insufficient heating of the MH storage system. The authors quoted that intermittent compared to continuous operation of the system provided better results in terms of hydrogen utilisation and thus overall vehicle performance (Davids et al., 2019). Kheirandish et al. (2014) studied the operation of a FCEB powered by a PEM FC with a MH storage. The experiments showed that during hydrogen desorption the temperature of the MH tank decreased from 25 to 0 $^{o}$C in less than 15 min resulting to hydrogen flow rate below the minimum required for FC operation. The authors suggested that the use of an external heater would decrease the overall efficiency of the system and concluded that a bigger MH tank or a compressed gas alternative would be the best solution (Kheirandish et al., 2014). The operation under real conditions of a FCEB suitable for urban mobility was assessed also by (Kovač and Paranos, 2019). The power system of the FCEB operated for 66 km consuming 4.5 $gH_2$ stored in the 350 NL MH tank. The refuelling flow rate was quoted at 2,000 cc min$^{-1}$, suggesting fast refuelling times for the users.

Acknowledging the above, it is apparent that MH storage in FCEVs might be an alternative solution, which can offer benefits but also raise concerns about proper implementation. Current developments of MH hydrogen storage allow its use in mobile applications with however better performance in smaller vehicles where hydrogen demand is not high, and the weight/cost of the MH tanks would not be an insurmountable obstacle. The refuelling cost in case of MH storage has been proved by previous studies that is different than the one of a compressed gas storage FC vehicle. To this end, the aim of this study was to investigate two refuelling SCs of MH-based storage of a FCEB to find the most viable and financially feasible one compared to a compressed gas refuelling alternative. Moreover, the research included the financial evaluation of the aforementioned SCs in two EU countries in order to appraise the prospects of hydrogen infrastructure from an economic point of view to support a future hydrogen market. The objectives above can be described by the following two RQs:

- Which is the refuelling cost the owner of a hydrogen light urban vehicle with MH storage should pay and how it is compared to the compressed gas storage counterpart?

- Would the hydrogen fuel price provided by refuelling-to-compressed hydrogen gas and to-MH HRSs differ in EU countries?

The structure of this paper consists of three main sections that include the methodology followed during the refuelling SCs development, the analysis of the data to elicit the results, and the discussion of the outcome to conclude if the RQs were answered and what is the study's addition to the existing knowledge.

### 5.4.2 Methodology

The methodology followed to gather and analyse the data to meet the objectives set in the previous section of this paper can be divided in two main parts. The first part included the gathering of the data used to describe the under investigation HRS types and subsequently the calculation of the respective hydrogen fuel cost in the case of a light FCEV using compressed hydrogen or MH hydrogen storage.

The hydrogen demand profile used during the this study was based on the results published by Apostolou et al. (2021) of a 200 W DC electric motor of a FCEB during a route of 27.8 km in the city of Huesca, Spain (Apostolou et al., 2021). The route was characterised mostly by small slopes and flat terrain and the average speed was 20.1 km/h with an upper limit of 25 km/h where the bike's DC motor operated. The FCEB used has an on-board compressed hydrogen tank under 30 bar of pressure. The hydrogen consumption (≈15 $gH_2$) results obtained from this route are presented and analysed in detail in (Apostolou et al., 2021).

The calculation of the hydrogen refuelling cost of the simulated light-duty FCEV (e.g. FCEB) to operate for 27.8 km depends on two main factors. Firstly, the quantity of stored hydrogen under compressed gas storage (i.e. 15.1 $gH_2$ at 30 bar of pressure) and MH storage, and the specifications of the HRS used for the refuelling process.

Although the hydrogen cost per kg provided by a HRS is not affected by the stored hydrogen quantity of a vehicle, the hydrogen demand affects the final price a consumer needs to pay following the law of demand/supply. According to Lototskyy et al. (2015), the residual hydrogen quantity of an $AB_2$ alloy used in MH storage for light-duty transportation is approximately 0.2 wt. % H (1 bar and $0^oC$), while the reversible hydrogen capacity of the MH material is on average 1.4 wt. % H at normal conditions (Lototskyy et al., 2015). This means that in order to meet the hydrogen demand of a FCEB operated under the same conditions of a compressed gas counterpart; the MH canister must be sized accordingly to accommodate and being able to deliver during normal operating conditions 15.1 $gH_2$. Based on the above, a MH alloy of 1.1 kg could be used to store approximately 17.5 $gH_2$ and deliver the required quantity of 15.1 $gH_2$.

To assess the financial aspect of the refuelling process between a compressed hydrogen and MH storage two SCs concerning HRS for light urban FCEVs such as FCEBs or FCESs were taken into consideration. The developed SCs were applied in two EU-28 countries, Denmark (DK) and Greece (GR) in order to financially evaluate the proposed project under different economic profiles.

- SC5.4.1: An on-site grid-connected HRS able to provide either compressed dispensed hydrogen of up to 100 bar of pressure or off-board MH hydrogen storage.
- SC5.4.2: An offsite HRS providing the same services as SC5.4.1.

The selection of the above SCs was based on the results from Apostolou (2020b) and Apostolou et al. (2021) whose results indicated firstly that grid-connected HRSs for small FCEVs are currently more financially profitable from an investor point of view and thus present lower refuelling prices. Secondly, the authors showed that the required components of those HRSs are minimised compared to stations with higher hydrogen flow rates and pressures, which serve larger vehicles, resulting as previously mentioned in lower investment and O&M costs (Apostolou, 2020b; Apostolou et al., 2021).

For the calculation of the refuelling cost for each SC, the NPV (Eqs. 4.2.37 and 4.2.38) of a 20-year (*n*) HRS investment for both SCs was calculated. The refuelling cost for getting the least positive NPV with a payback period not exceeding 10 years indicated the value for each case (i.e. compressed and MH hydrogen storage). During the NPV calculation, it is assumed that the annual hydrogen delivered in SC5.4.2 was equal to the annual hydrogen production by the electrolyser of SC5.4.1 and that the entire hydrogen fuel in both SCs was sold to consumers. The data used for the calculation of the NPV are presented in Table E1 (Appendix E).

The small-scale HRS was assumed to have one dispenser for the compressed delivered hydrogen, while for the MH storage case, a simpler dispensing unit is required due to low pressures. The components of the HRS included also a 50 kW PEM electrolyser, a buffer storage tank at 20 bar, a 2.3 kW hydrogen compressor with a suction and outlet pressure of up to 20 and 100 bar respectively and a high pressure storage tank at max. 350 bar (Table 5.4.1), while the refuelling pressure was set to 30 bar (Apostolou et al., 2021). A price for normal quick coupling connectors that are extensively used for charging MH canisters is approximately 100 €/connector (Staubli systems GmbH, 2018). It is assumed that a system of three connectors and its auxiliary components (e.g. valves, pipes) would cost €1,000. The main components employed for the HRS in both SCs are depicted in Figs. 5.4.1 and 5.4.2. The dashed lines correspond to the compressed hydrogen gas refuelling case. For the calculation of the HRS investment cost, Eqs. 5.4.1 and 5.4.2 are used.

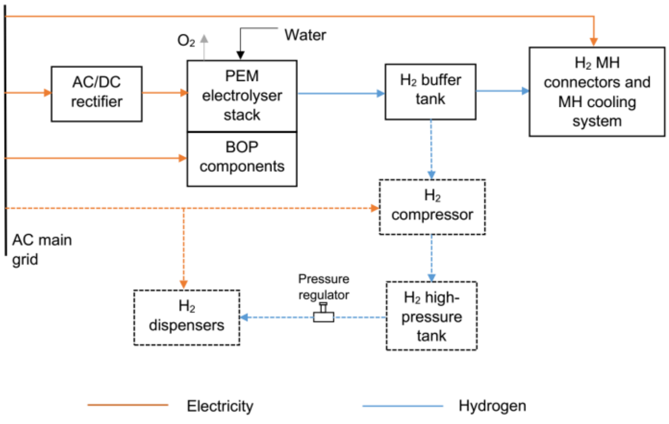



Fig. 5.4.1. Schematic representation of the HRS for SC5.4.1.

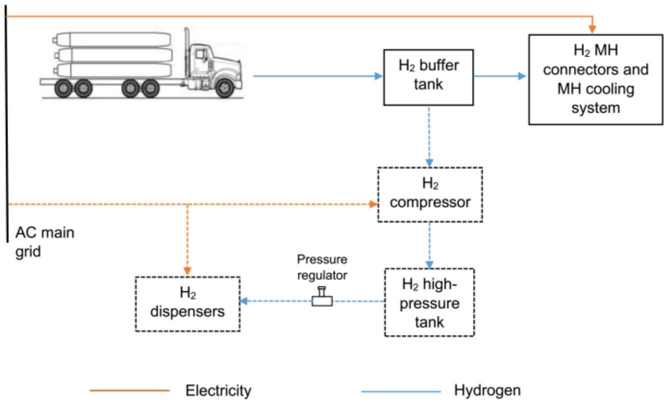



Fig. 5.4.2. Schematic representation of the HRS for SC5.4.2.

The footprint of the HRS for both SCs concerning the compressed hydrogen storage refuelling case is assumed to be 300 m$^2$, while for the MH refilling topology the footprint has been assumed to be 100 m$^2$. The daily operating hours ($h_{operat}$) of the HRSs for both SCs have been assumed to be 13 h (08:00 to 21:00), with two employers working on shifts. Hence, the total operating hours of the HRSs components throughout the project's duration are calculated to approximately 95,000 h. Based on Perez and Casero (2019) the operating hours of a PEM electrolyser may reach 80,000 h suggesting that during the lifetime of the project, a stack replacement would be necessary (Perez and Casero, 2019). For the investment, a loan to total capital investment ratio has been taken into account to be 0.5, and the loan re-payment time has been accounted to be 10 years.

The cooling system of the HRS for MH canisters storage topology was assumed able to accommodate a 10 min refuelling time during each process. Based on a formation enthalpy of a low temperature $AB_2$ MH tank ($\Delta H^o$ = –21.57 kJ/mol $H_2$), the produced heat during the absorption of 1 kg of hydrogen is estimated to approximately equal to 10 MJ (Lototskyy et al., 2016b). By considering the 10 min of refuelling time, 16.6 kW of cooling capacity of the MH is required. Contemporary air source heat pumps present an average COP of 3 for low ambient temperatures (Nie et al., 2017), indicating that the electric power required for this system would be approximately 5.5 kW. In contrast, in the case of compressed hydrogen gas refuelling process, a cooling system is not required due to the low refuelling flow rate ($\leq$ 20 Nm$^3$/min) (Ulleberg and Hancke, 2020). Additionally, the refuelling dispenser due to the low flow rate and a refuelling pressure up to 300 bar is assumed to cost as much as a compressed natural gas dispenser (Apostolou et al., 2021). The mass capacity of both the buffer and high-pressure storage vessels was set to be equal to the maximum daily hydrogen production of the PEM electrolyser. Based on the maximum outlet hydrogen flow of the electrolyser (see Table 5.4.1) and the operating hours of the station, the daily hydrogen production ($M_{H2}$) can be estimated to 16.6 $kgH_2$.

Table 5.4.1. Specifications of the main components of the HRS.

| **Parameter** | **Power (kW)** | **Max. outlet $H_2$ flow rate ($Nm^3/h$)** | **Max. outlet pressure (bar)** | **Mass capacity ($kgH_2$)** |
|---|---|---|---|---|
| PEM electrolyser (incl. BOP) (Perez and Casero, 2019) | 50 | 14.2 | 20 | - |
| $H_2$ compressor | 2.3 | 11.2 | 100 | - |
| $H_2$ buffer tank | - | - | | 16.6 |
| $H_2$ high pressure tank | - | - | | 16.6 |
| MH cooling system | 5.5 | | | - |

$$IC_o = IC_{el}\,P_{max} + IC_{comp}\,P_{comp} + IC_{bfr}\,M_{H2bfr} + IC_{H2stor}\,M_{H2hp} + IC_d + IC_{MHsys} + IC_{constr} \tag{5.4.1}$$

$$IC_{constr} = (IC_{el}\,P_{max} + IC_{comp}\,P_{comp} + IC_{bfr}\,M_{H2bfr} + IC_{H2stor}\,M_{H2hp} + IC_d + IC_{MHsys}) * (f_{cost,constr} + f_{cost,cont}) \tag{5.4.2}$$

In both SCs, $IC_{comp}$, $IC_{H2stor}$ and $IC_d$ are valid for the compressed hydrogen refuelling case. Additionally, $IC_{el}$ is applied only in SC5.4.1, and in both SCs $M_{H2bfr} = M_{H2hp} = M_{H2}$

The calculation of the annual O&M costs (Eq. 5.4.3) was taken as a percentage of the investment cost (maintenance cost) plus the annual energy consumption of the system estimated through Eq. 5.4.4, and the delivered hydrogen cost, valid for SC5.4.2. $Ec_{MH,cool}$ corresponds to the MH refuelling process, while the electricity consumption of the dispenser in the compressed hydrogen refuelling process is considered negligible due to no cooling system.

$$FC_{OM} = FC_{par} * IC_o + E_{cons} * Rel + M_{H2} * FC_{H2} \tag{5.4.3}$$

$$E_{cons} = 365 * M_{H2} * (Ec_{electr} + Ec_{comp} + Ec_{MH,cool}) \tag{5.4.4}$$

In SC5.4.2, the hydrogen fuel is delivered to the HRS with a cost including the production and distribution of hydrogen. According to (Apostolou, 2020a), the average cost of hydrogen fuel produced from a centralised electrolysis plant in Denmark under continuous operation has been calculated to approximately 4.1 €/$kgH_2$. The price of ‘green’ hydrogen in Europe is estimated by IEA between at 2.5 and 6.0 €/$kgH_2$, indicating a similar to DK price (IEA, 2019c). The distribution cost from a centralised production unit located 500 km away from the delivering spot equals approximately to 1.7 €/$kgH_2$ (IEA, 2019c). Hence, the total hydrogen fuel cost delivered to the offsite HRS (SC4.2) for both DK and GR is assumed to be equal to 5.8 €/$kgH_2$.

### 5.4.3 Results and discussion

The estimation of the quantity of hydrogen required to be stored in the MH tank as presented in the previous section of this article equals to 17.5 g$H_2$ in order to secure a range of the FCEB similar to the one of the compressed hydrogen storage counterpart. To this end, it is apparent that from the consumer's perspective the actual cost that is necessary to cover for getting the same autonomy would be higher.

In the context of the second RQ of this study, two HRSs types able to provide hydrogen fuel to light-duty FCEVs such as FCEBs with different on-board hydrogen storage technologies (i.e. compressed gas and MH storage) were assessed to find the lowest hydrogen fuel cost for getting a financially viable business case (i.e. positive NPV). The results of the calculated hydrogen fuel cost corresponding to a positive NPV for both DK and GR are presented in Fig. 5.4.3. The calculated financial parameters for the respective HRS types for both countries are presented in Tables 5.4.2 and 5.4.3.

Table 5.4.2. Financial results of the under investigation HRSs in DK.

| | **SC5.4.1 compressed gas storage** | **SC5.4.1 MH storage** | **SC5.4.2 compressed gas storage** | **SC5.4.2 MH storage** |
|---|---|---|---|---|
| **$IC_o$ (€)** | $2.92\ 10^5$ | $2.07\ 10^5$ | $9.99\ 10^4$ | $1.43\ 10^4$ |
| **$H_2$ price (€/kg$H_2$)** | 34.8 | 31.2 | 30.0 | 27.4 |
| **NPV (€)** | $1.43\ 10^5$ | $6.94\ 10^4$ | $1.18\ 10^4$ | $5.09\ 10^3$ |
| **PP (y)** | 9 | 9 | 8 | 1 |

Table 5.4.3. Financial results of the under investigation HRSs in GR.

| | **SC5.4.1 compressed gas storage** | **SC5.4.1 MH storage** | **SC5.4.2 compressed gas storage** | **SC5.4.2 MH storage** |
|---|---|---|---|---|
| **ICo (€)** | $2.92\ 10^5$ | $2.07\ 10^5$ | $9.99\ 10^4$ | $1.43\ 10^4$ |
| **$H_2$ price (€/kg$H_2$)** | 24.8 | 20.5 | 17.2 | 14.2 |
| **NPV (€)** | $7.59\ 10^4$ | $4.86\ 10^4$ | $2.65\ 10^4$ | $4.31\ 10^3$ |
| **PP (y)** | 9 | 9 | 9 | 1 |

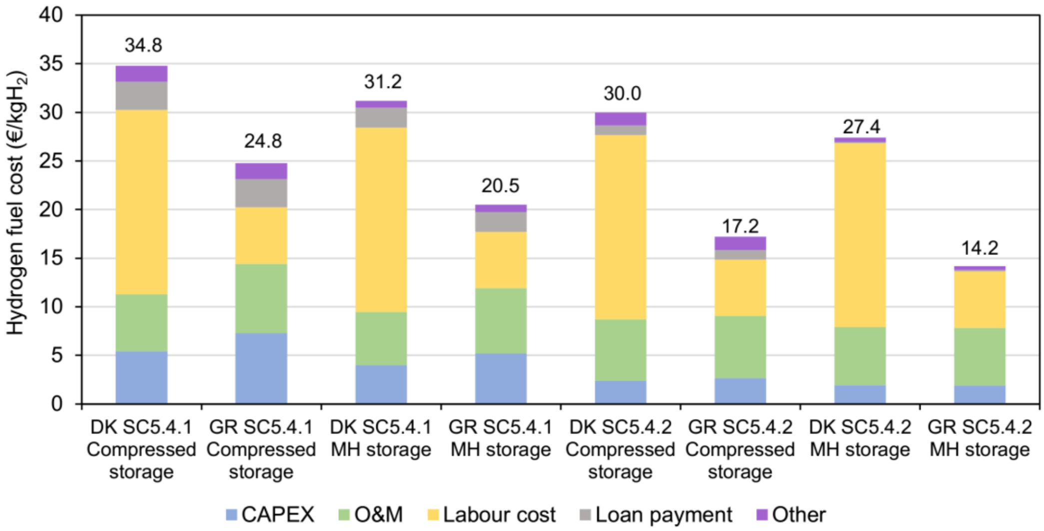



Fig. 5.4.3. Refuelling cost of hydrogen fuel for SC5.4.1 and 5.4.2 in DK and GR.

The breakdown costs depicted in Fig. 5.4.3 represent the first year of the 20-year operation of the proposed HRS types, where the expenses of the stations operation influence the final hydrogen fuel price for each station type.

Based on the results presented in Fig. 5.4.3 it is apparent that for having a financially viable business, the hydrogen fuel cost in DK is higher than in GR. Although the HRS components costs are considered the same for both countries (Table E1, Appendix E), other parameters such as labour costs, electricity prices, and corporate taxation affected the final fuel cost results.

The CAPEX represents the before-tax revenues of each business SC that are used to pay back the investment cost ($IC_o$) during the PP, which is documented in Tables 5.4.2 and 5.4.3. According to Fig. 5.4.3, the business revenues in the case of GR are higher than the ones of the respective SCs and types of HRS. This is happening because although the CAPEX is similar for the same HRS type, corporate taxation in GR is higher compared to DK. In this context, the before-tax revenues of the respective HRS types in GR need to be higher than those in DK in order to pay back the investment cost before the set 10-year period.

The O&M costs in SC5.4.1 include a significant electricity consumption due to the hydrogen production and compression processes. Due to the higher cost of electricity in GR, the O&M costs in GR present a higher share in the final fuel cost. However, what actually plays the most significant role in the cost difference of the hydrogen fuel is the labour cost, which in GR compared to DK is almost three times lower. To this end, although O&M costs and taxation in GR is higher than DK, the final cost of the fuel is substantially lower.

On the other hand, the O&M costs in SC5.4.2 present a similar value for the respective HRS types in both countries as the electricity consumption is minimised only to the one of the compressor operation in the compressed gas storage case. The major expenditure of the O&M costs consists of the hydrogen delivered to the HRS from the centralised production facility. Similarly to SC5.4.1, the main difference of the hydrogen fuel cost between the two countries in SC5.4.2 lies on the significant difference in the labour cost, while the other factors for the respective station types are almost similar.

As it was expected, the hydrogen fuel cost in SC5.4.1 compared to SC5.4.2 in both counties is higher due to the higher $IC_o$ (see Tables 5.4.2 and 5.4.3) resulting to increased loan payment and before tax revenues. Furthermore, due to the lower $IC_o$ and the specifications of the offsite HRSs, the loan payment and 'Other' (land lease, insurance) costs are lower in SC5.4.2 that reduces further the final hydrogen fuel cost.

Acknowledging the results presented in Tables 5.4.2 and 5.4.3 and the hydrogen stored in the respective storage technologies, Fig. 5.4.4 shows the total refuelling costs of the under investigation FCEB's with MH storage and compressed gas (at 30 bar) a consumer needs to pay in order to get the same autonomy.

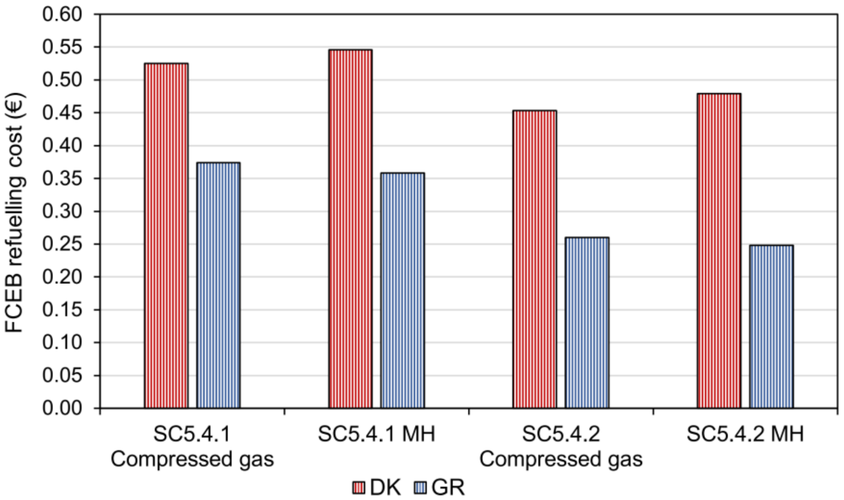



Fig. 5.4.4. Final refuelling cost of a FCEB for both storage technologies in the respective countries.

Based on the results presented in Fig. 5.4.4, three main conclusions could derive. First, as it was mentioned above, the refuelling cost of a FCEB would be higher in DK compared to GR due to the reasons analysed in the elaboration of Fig. 5.4.3 data. Second, the refuelling cost by an offsite HRS is similarly calculated to be lower than the on-site counterparts for both SCs 5.4.1 and 5.4.2. However, the third observation shows clearly a higher final cost of the MH storage technology in DK, while for GR the refuelling cost remains almost the same for both storage technologies. This shows that although the hydrogen cost per $kgH_2$ for the hydrogen-to-MH HRS is lower in both SCs compared to the compressed gas storage alternative, the final cost a consumer is called to pay to get the same autonomy is higher in the MH topology. Hence, the inherent characteristic of MH suggesting that utilising the full capacity of the stored hydrogen may happen under certain conditions that are difficult to be achieved in small FC applications such as FCEBs, introduces an extra cost due to the higher quantity of hydrogen that needs to be stored in order to meet the power demand. In the context of the MH stored hydrogen technology, the lower hydrogen fuel price advantage at the HRS dispensers is diminished by the higher hydrogen fuel required to achieve a similar autonomy with the compressed gas technology.

### 5.4.4 Conclusions

This study investigated the financial aspects of the refuelling processes of a light-duty urban FCEV such as a FCEB by comparing two hydrogen storage technologies including compressed gas and MH storage. The methodology followed was based on the estimation of the hydrogen fuel cost to get a positive NPV of two business SCs including on-site and offsite HRS topologies. To get a more detailed overview in regards to how the refuelling costs are influenced, apart from the on-board hydrogen storage technologies, by external factors such as labour and O&M costs, the SCs were investigated for two EU countries presenting different economic indicators. The main results showed that MH configuration could provide cheaper fuel to consumers but with higher refuelling times, while offering an appealing investment to future investors. However, the final cost the consumer is called to spend at the end is higher compared to gas storage due to the increased hydrogen quantity that needs to be stored in the MH tank to get the same autonomy as the one achieved with a compressed gas storage. Additionally, it was revealed that the hydrogen cost dynamically alters between countries due to external factors such as corporate taxation, labour costs, and electricity prices. MH storage seems promising for small vehicles where the hydrogen demand is low and thus the weight of an on-board tank will not be an obstacle in the performance of the vehicle. Nevertheless, conditioning of the MH hydrogen release to the FC of a light vehicle should be further investigated to secure the least hydrogen residual and uninterrupted FC operation during the desorption process.

# 6. Developing a techno-economically feasible infrastructure to support hydrogen light-duty mobility in urban environments

In this chapter, the main findings of the documented articles that were presented in the previous sections are integrated and aligned to the stated RQs of this PhD dissertation. The aim to identify among all business SCs of RES-produced hydrogen to be used in light-duty transportation, an economic viable solution to support a fleet of urban-oriented vehicles such as FCEBs or FCESs is described by the general question: 'How hydrogen refuelling infrastructure coupled with RES could support light-duty mobility in urban environments?'

Each RQ analysed in the respective articles used to investigate the main objectives of this research could be said to be a part of a 'pyramid' where the base is represented by the energy and environmental aspects presented in Fig. 1.1. The main core is represented by the RQs that were introduced to cope with the major problem as defined from the 'pyramid' base, while the top could be described by the general question as stated in the previous paragraph.

## 6.1 The socio-economic prospects of the light-duty FCEVs' market and its respective infrastructure

In the context of the first RQ of this thesis, two journal articles for assessing the advantages, drawbacks and prospects of the hydrogen transportation market were introduced. The first article's objective was to identify and document the status and future prospects of hydrogen technologies in the transportation sector based on the international peer reviewed literature. According to the documented literature, the specific study provided an assessment on the forecasts concerning the evolution on the one hand of the vehicle and refuelling station numbers and on the other, the financial factors and refuelling prices. The main findings can be quoted as follows:

- There are several types of HRSs that could be implemented in the hydrogen transportation market and can be distinguished by production technology, place of production, fuel capacity and delivering pressure.

- There is a bi-directional negative relationship of FCEVs and HRSs. Lack of adequate infrastructure hinders the increase of the FCEVs numbers and vice versa.

- The capital cost of HRSs depends mostly on the type of the station and for commercialised vehicles and low capacity stations it currently ranges between approximately €1.0 million and €3.5 million.

- The future capital costs (in 2030) of large capacity HRSs are expected to decrease by up to 40%.
- Current levelised costs of fossil fuel derived hydrogen fuel at the pump ranges between 10 and 15 €/kg$H_2$.
- Future cost (after 2040) of RES-based hydrogen fuel is expected to stabilise and range between 4 and 7 €/kg$H_2$ depending on the HRS type.

The results of the first journal article indicated that the potential of hydrogen technologies in the transportation sector present a decreasing trend in terms of infrastructure and ownership costs. Three SCs for the future evolution of the global HRSs numbers by 2050 have been presented; an optimistic with approximately 250,000 HRSs, a moderate with 50,000 HRSs, and a pessimistic with less than 20,000 HRSs. Regarding the CAPEX of HRSs, the SCs indicated an increase of the cost in the mid-2020s due to moving from fossil fuel-based central production to RES on-site based production of the hydrogen fuel. The hydrogen fuel cost on the other hand was assessed to present a decrease in two identified SCs that will stabilise by 2050 below 7 €/kg$H_2$.

Hence, based on the international literature, the potential of hydrogen mobility share in the passenger fleet mix was found to play a significant role towards the decarbonisation of transport. However, apart its recognition among the ranks of the market shareholders, its establishment in the future market passes through the acceptance of this technology by the end users i.e. the public.

The second journal article in the context of the first RQ investigated the perspective of the public towards hydrogen mobility. The research focussed on Denmark with however providing a methodology that could be applied to a greater extend. The outcome of this study can be addressed as follows:

- Limited knowledge about hydrogen technologies in transportation affects the public’s propensity to invest in FCEVs.
- The refuelling infrastructure needs to be significantly enhanced in order to support a developing hydrogen mobility market.
- The Danish public believes that FCEVs are as safe as conventional vehicles.
- The environmental attitude of the public influences the willingness of people to purchase a FCEV.

- The capital cost of the FCEVs consists of a barrier in the expansion of the market even in an economy as Denmark with a GDP among the first three of the EU-27 countries (Eurostat, 2020b).

- The cost of fossil fuel-derived hydrogen fuel is not considered a significant barrier in the expansion of the hydrogen transportation market.

- The almost absent media support on hydrogen transportation limits the prospects of the market as the public awareness on this technology remains confined to the basics.

The compiled empirical study as presented in the second quoted paper showed that the public in Denmark identifies hydrogen mobility as a feasible alternative to conventional transportation with however noting the drawbacks that this technology is believed by the public to has. Most of the aforementioned results could be said to be valid for most countries including the technology awareness, media support, infrastructure and vehicles' cost. On the other hand, other factors identified not to pose an impact on the prospects of FCEV market such as the individual's income and the hydrogen fuel cost, are directly affected by the financial factors of each country and need to be further investigated.

In conclusion, the investigation of the first RQ through addressing the respective FCEV and refuelling infrastructure potential in the current and future market revealed a two-axis perspective of the problem. First, the economic aspect of the hydrogen transport market where the technology development and maturity will allow economies of scale and consequently a price reduction to introduce competition with other already established technologies. Second, the social aspect of accepting this technology as one of the most feasible alternatives in the transportation sector. This will occur through technology readiness and awareness that can be achieved only if the economic factors would secure viable businesses and impel the respective shareholders to support such an initiative.

## 6.2 An economically viable ‘green’ hydrogen production system in the wind power and electricity markets to support sustainable light-duty hydrogen transportation

The second RQ of this dissertation was investigated through two journal articles including a literature review and a feasibility study of coupled wind power and hydrogen production-utilisation systems either for electricity grid re-powering services or for delivering hydrogen transportation fuel. The main core of the first paper was the evaluation of the state-of-art of coupled WH systems by examining three different topologies. First, grid connected WH systems allowing higher penetration of wind power in the electricity grid, second stand-alone systems that can be applied in autonomous networks, and third WH topologies to produce ‘green’ hydrogen fuel for transport applications. The outcome of the literature review can be quoted as:

- The round-trip efficiency of WH topologies depends on the application. For grid support utilities, round-trip efficiency is the lowest and may be as low as 30%. The efficiency for producing and storing the hydrogen fuel ranges between 50% and 65% and depends on the electrolysis technology and the compression/storage processes.

- The hydrogen fuel cost was found to present a wide range of values between 4 and 26 €/kg$H_2$, due to a number of factors including the size of the system/demand of the fuel, the technology of production, and the primary energy used to produce hydrogen (i.e. fossil fuel, conventional/RES produced electricity).

- The implementation of WH systems contributes to the avoidance of a significant amount of $CO_2$ emissions in the energy and transportation sectors.

The main conclusion of this paper was that hydrogen technologies are more economically viable when used not entirely for RES energy storage but as a multifunctional service provider that would include the transportation market as the one of the many end-users. This stems from the fact that on the one hand, the grid ancillary service presents low efficiency, and the capital cost of the required systems is high, which indicate possible financial complications in a future business attempt. On the other hand, the demand of hydrogen fuel in transportation, industry and other utilities presents an increasing trend, which is expected to be further enhanced in the next decades. The implementation of WH configurations has been reported to play a critical role in the decarbonisation of the energy and transport sectors. Depending the size of the WH system, LC GHG emissions avoidance could reach 1.78 kg$CO_2$-eq/kg$H_2$, suggesting the environmental benefits of such investments. To this end, a future business of a hydrogen system being able to provide multiple services seems to be a financially feasible venture and enhance environmental sustainability.

The second journal article aiming to address RQ2 investigated the prospects of a WH system participating in the electricity and transportation markets. Three SCs were identified; in the first one, the repowering service back to the electricity grid through a FC electricity provider participating in the electricity market was assessed in terms of financial viability. In the second, the hydrogen production process was added to the topology and the configuration participated apart from the electricity market in the transportation market too as a centralised fuel provider. The third SC examined the participation of the hydrogen production system alone in the electricity market as a demand-response load and in the transportation market alone as a fuel provider. To develop the above-mentioned SCs, simulation models of the electrolysis and the FC processes able to interact with the electricity market parameters including available energy/excess wind energy, and electricity prices were developed and applied in the Danish electricity market. The outcome of this research can be summarised in the following points:

- The developed algorithms can be applied in any electricity market by altering the respective inputs concerning energy and financial parameters. The output of the combined algorithm provides the cost of hydrogen fuel based on the inputs.

- Participation of the hydrogen system only in the Danish electricity market for ancillary services is not economically viable. To secure a viable business SC, the capital and O&M costs need to be reduced or electricity prices need to substantially increase.

- A hydrogen system participating in both markets is economically viable with an average selling price of the hydrogen fuel in the transportation market of approximately 4.5 €/kg$H_2$ for continuous operation of the hydrogen generator and 84 €/kg$H_2$ for operation during excess wind power.

- The average hydrogen price to have a feasible business SC in the case of a hydrogen system participating only in the transportation market was calculated to approximately 4.0 €/kg$H_2$ for continuous operation, while for operation only during excess wind power was calculated to 13.7 €/kg$H_2$.

The results of this paper indicated that the best economic factors securing a viable business was succeeded with a continuous operation of the hydrogen production system and participation in the transportation market alone. Financial viability of a hydrogen system in Denmark corresponds to high hydrogen costs in the case of operation during excess wind power but this is dynamically affected by the amount of the excess wind power, which is expected to increase in the next decade.

In conclusion, it can be said that a hydrogen system in Denmark under either continuous operation or operation only during excess wind is currently economically feasible in the following cases:

- For participation in the demand/response electricity market as a consumer (load) and as a fuel provider in transportation market with a low-end hydrogen fuel cost comparable to the high-end price of fossil fuel based hydrogen production.

- In participation in the electricity market both as a consumer (during hydrogen production) and a commitment unit (re-powering unit) and in transportation market as fuel provider but under continuous operation during the hydrogen production phase. Although continuous operation is not in general entirely connected to the wind power market, the Danish electricity system is highly based on wind power suggesting that even under continuous operation of the system; a large share of the electricity input to the water electrolysis system would come from WTs.

## 6.3 Economically feasible hydrogen refuelling infrastructure for cycling-based transportation from an investor and customer perspective

The final RQ that has been examined in this dissertation aimed to identify the best business case SC of refuelling infrastructure to support light-duty urban hydrogen mobility. Based on the results analysed in the previous section, a hydrogen production system in Denmark to provide hydrogen fuel to transportation could be a financially viable SC. However, these results revealed the one side of the coin, regarding hydrogen production without all the necessary processes occurring in hydrogen refuelling processes. To this end, the techno-economic and social analysis of the last part of the hydrogen fuel supply chain to support urban hydrogen transportation was presented via the results of four journal articles. The first article included the investigation of an autonomous on-site hydrogen refuelling station in the city of Herning, Denmark, where based on the wind resource of the region and a hypothetical hydrogen demand, the sizing of the HRS's components to meet the fuel demand of the city was computed. The outcome of the paper can be documented as:

- A sizing algorithm for all the HRS components combined with the developed hydrogen production and price estimation algorithms presented in the second paper addressing RQ2 consists of a tool to appraise future business SCs.

- An estimated hypothetical annual hydrogen demand to support urban hydrogen mobility in the city of Herning equals to 2,291 $kgH_2$.

- The model calculations showed that a 50 kW WT and a 70 kW water electrolysis could cover the hydrogen daily demand in 322 out of 365 days.

- The annual hydrogen production available calculated to 2,896 $kgH_2$.

- The hydrogen fuel cost to secure a viable business case SC for an autonomous HRS in Herning found to equal at least 50.2 €/$kgH_2$.

Based on the findings of this research, it seems that the wind resource of a region where an autonomous HRS is designed to be implemented is very important, as this would play significant role on the day-by-day operation of the station and to secure a constant fuel supply. It seems that although the final annual production of hydrogen exceeds the annual demand, the daily demand is not always covered as it depends on the wind conditions of the region. The higher annual production compared to the hydrogen demand is due to the oversize of the system to meet most of the average fuel demand requested on a daily basis.

The second and third paper addressing the final RQ consisted of simulated and experimental investigation of the operation of a FCEB under different refuelling pressure SCs. The examined refuelling pressure values were 30, 100, 150, and 200 bar, and the main scope of both studies was to find the least hydrogen fuel cost for the consumers without however compromising the investment's viability. The investigated refuelling SCs consisted of:

- An experimental low-pressure refuelling process from a small-scale hydrogen generator powered from the electricity grid.
- A simulated and experimental low pressure refuelling process from an autonomous HRS.
- Simulated low pressure and experimental low-to-high pressure refuelling processes from a grid-connected on-site HRS.

The second quoted article in the context of the third RQ included all the simulated HRS refuelling processes and the experimental low-pressure refuelling pressure from a small-scale hydrogen generator as examined for a hypothetical case study for the city of Herning, Denmark. The derived results were then compared to other vehicle types used for urban transportation. Additionally, one of the objectives of this article was to assess the operation of a FCEB as expressed by different users. The results of this study can be summarised as:

- The FCEB users claimed that this type of urban mobility presents an alternative able to cover their daily commuting needs.
- The refuelling cost the FCEB users are willing to pay ranged between 0.036 and 0.103 €/km.
- The energy consumption per km for the first refuelling SC ranged between 0.026 and 0.038 kWh/km. The respective cost is calculated between 0.008 and 0.012 €/km. Due to the low hydrogen outlet flow rate, the refuelling time exceeded one hour.
- Based on the results of the first paper analysed to address RQ3, the cost of hydrogen fuel per km for the second refuelling SC was found to range between 0.015 and 0.025 €/km.
- The hydrogen cost delivered by a grid-connected on-site HRS was calculated to range between 22.1 and 32.7 €/kg$H_2$ depending on the size of the hydrogen system, while the average cost per km was quoted to approximately 0.010 €/km.

- The low end of the hydrogen cost per km corresponds to the case where the FCEB operates entirely on hydrogen without the addition of a buffer battery fully charged from the on-board stored hydrogen.

- The refuelling time of the on-site HRSs for the refuelling process, excluding the buffer battery-charging phase, is approximately one minute.

- The refuelling cost per km of a FCEB was found in the first and third SC to be comparable to the one of BEBs and lower than the other vehicle types of urban transportation. However, the refuelling time of a FCEB was assessed to be significantly lower than the recharging process of a BEB.

The documented results from this paper clearly show that the most appealing SC from the consumer (i.e. FCEB user) perspective comprised the grid-connected on-site topology because although the hydrogen fuel cost per km presented a value similar to the upper-end of the one derived from a small-scale generator, the refuelling time was found to be significantly lower.

The determination of the hydrogen fuel cost under high-pressure refuelling as well as the experimental verification of the low-pressure refuelling simulated results for a grid-connected large-scale HRS was conducted and presented in the third article addressing RQ3. The experimental results were then presented in a workshop to bicycle commuters who were asked to provide feedback on their opinion of the refuelling costs of a FCEB according to their everyday commuting needs. The outcome of the paper is summarised in the next bullet points:

- Hydrogen cost for 30, 100, 150 and 200 bar of refuelling pressure HRS is calculated to 34.7, 36, 36.1, and 36.9 €/kg$H_2$ respectively.

- The minimum hydrogen cost per km to have a viable business case (positive NPV and PP under 10 years) was calculated to be the same for all refuelling pressures at approximately 0.019 €/km.

- The workshop's participants answered that although the cost per km is the same, they prefer the low-pressure refuelling process due to lower total refuelling costs as their daily commuting needs allow a refuelling process once per week.

- Low-pressure infrastructure also presents the lowest investment and O&M costs from the investors' perspective.

The hydrogen cost of the simulated grid-connected HRS compared to the one calculated during the experiments was lower due to the size and demand of the system. The experimental calculations were based on a 50 kW water electrolysis system able to produce annually 6,059 $kgH_2$ (based on Table 5.3.1), while the simulated electrolysis system was based on theoretical data based on a case study where the annual hydrogen fuel demand would reach 8,614 $kgH_2$.

## Comparative analysis between grid-connected and autonomous on-site HRSs

The results of the above-mentioned article identified that a grid-connected on-site HRS is the most appealing solution from the investor and the consumer perspective to meet the hydrogen demand of a similar to Herning city for urban commuting trips by light-duty vehicles as FCEBs. In the Danish investigated case study, a grid-connected water electrolysis system constitutes a ‘green’ hydrogen production process as most of grid electricity is coming from RES.

However, in the case where the electricity mix is not based on RES, an autonomous on-site HRS to support light urban mobility would comprise the only source of ‘green’ hydrogen. To this end, it was deemed important to provide a comparison of the hydrogen fuel costs between the grid-connected on-site HRS with an autonomous powered counterpart.

The sizing algorithm used to size the main system components including the WT, the water electrolysis system, and the storage configuration was based on Section 5.1. The algorithm used took into consideration a similar hydrogen fuel demand to the one identified in Section 5.3 (i.e. 6,059 $kgH_2$). The sizing result indicated a WT and an electrolyser of rated power of 100 kW and 113 kW respectively able to annually produce approximately 6,000 $kgH_2$. The reason for the difference between the hydrogen demand and the real hydrogen production was explained in the analysis of the first paper addressing RQ3 in section 6.3.

To calculate the respective hydrogen fuel costs, the algorithm for the financial evaluation of an autonomous HRS presented in Section 5.2 was applied to the same case study examined in Section 5.3 (i.e. third article addressing RQ3).

Table 6.1 and Fig. 6.1 present the results of the applied algorithm for the autonomous on-site HRS compared to the ones of the grid-connected counterpart.

Table 6.1. Hydrogen refuelling costs for having a viable business SC of an autonomous and a grid-connected HRS in Denmark

| | Hydrogen fuel cost (€/kg$H_2$) | | | |
|---|---|---|---|---|
| **Hydrogen refueling process SCs** | **30 bar** | **100 bar** | **150 bar** | **200 bar** |
| Grid-connected HRS | 34.7 | 36.0 | 36.1 | 36.9 |
| Autonomous HRS | 37.0 | 38.2 | 38.3 | 39.1 |

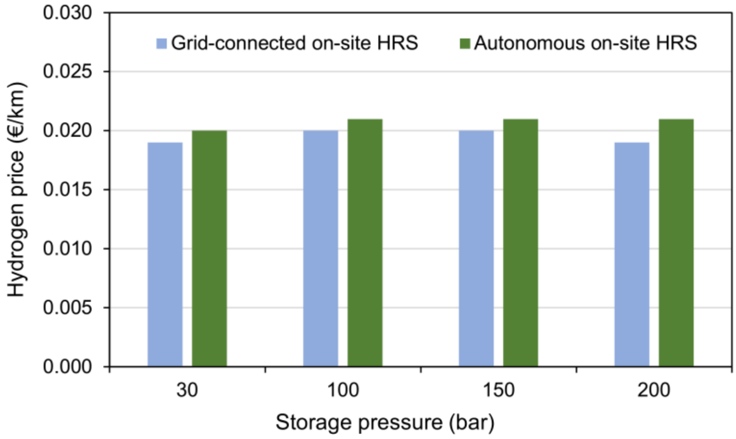



Fig. 6.1. Comparison of the hydrogen cost per km between grid-connected and autonomous on-site HRS.

Based on the results presented in Table 6.1, the hydrogen cost to have a viable business SC for an autonomous on-site HRS is higher than a grid-connected HRS counterpart is. This means that in the case of an autonomous HRS, the avoidance of the electricity expenses for producing hydrogen found in a grid-connected system in Denmark does not counterbalance the distributed in a 20-year project investment cost of a WT inclusion. However, it should be noted that in the case of installing an autonomous HRS at a region with better wind resource than the one investigated in this case study, would result to a different sizing of the WT to meet the energy demand (requirement of a smaller WT). Thus, the investment costs for providing the same hydrogen production would be lower resulting to a hydrogen price that could be even lower than the grid-connected HRS option.

On top of that, what can be said is that according to Fig. 6.1, although the price of hydrogen in the autonomous HRS is higher than the grid-connected system, the hydrogen cost per km difference is considered insignificant. Hence, from the consumers' point of view, both solutions to secure a hypothetical hydrogen demand could be considered similar. On the other hand, the investment cost of these two different types of HRS is significantly different with the autonomous HRS ranging between €679,300 and €738,900 and the grid-connected between €136,510 and €188,740, indicating that from an investor's point of view, a grid-connected SC looks more appealing.

## Comparative analysis between grid-connected HRS with compressed gas refuelling process and a metal hydride refuelling process

The fourth article to examine what type of HRS would be the most economically feasible from both the consumer's and investor's perspective included the investigation of the refuelling processes of a FCEB with on-board MH storage instead of compressed gas storage. The required components for MH refuelling were assessed in the article and a comparison with the already studied compressed gas hydrogen refuelling processes of a FCEB in the context of RQ3 was documented. Moreover, in order to assess the best HRS type for light-duty urban vehicles, the comparison also included an offsite HRS. The economic algorithm was applied in two EU countries presenting different economic profiles to provide an overview of how hydrogen economy could be developed in different countries. The main results of this paper can be summarised as:

- The hydrogen fuel cost for the under investigation HRSs is higher in countries where external factors such labour cost and O&M costs are higher.
- The investment cost and PP of compressed gas HRSs is significantly higher than the delivered-to-MH HRSs.
- The offsite HRS presents lower investment and hydrogen fuel costs.
- The investment cost of the same type of HRSs is approximately the same for EU countries.
- The hydrogen fuel price per kg is lower for the delivered-to-MH stations compared to compressed gas stations.
- The final refuelling cost a consumer needs to pay to refuel an on-board MH tank to have the same autonomy with the compressed-gas tank counterpart is the same or higher.
- The refuelling time of MH is significantly higher than the one of compressed gas refuelling process.

The outcome of this paper showed that MH storage technology is very promising for small vehicles in terms of refuelling cost and HRS business perspective. However, the inherent problem of contemporary MH storage technology of not being able to release the entire stored hydrogen quantity at normal conditions necessitates the storage of higher quantities of hydrogen to meet the same power demand as the one from a compressed gas counterpart. To this end, the final cost that burdens a consumer would be the same or even higher than a vehicle with compressed gas tank.

Drawbacks of MH in transportation include additionally to high cost, long recharging time and large weight. Hence, only vehicles with low hydrogen demand could benefit from such technology as weight could be optimised to meet the demand, and refuelling time could be minimised down to some minutes depending on the material used, and the refuelling standards (cooling of the tank, suitable hydrogen outlet flow rates of the dispenser).

The hydrogen light-duty urban refuelling economics in terms of fuel cost are proved to differ among countries with different financial indicators. Although the investment cost of HRSs is in general the same for EU countries, the O&M costs play significant role in the final fuel price the consumer is called to pay.

Offsite low-pressure HRS topologies for light-duty urban transportation seem to offer the best solution from an investor and consumer point of view and this can be considered true in the Danish case study where most of electricity comes from RES. As long as the centralised hydrogen production facility is based on a water electrolysis system participating in the electricity market as a consumer (i.e. load demand/response role), the offsite HRS type delivering compressed gas hydrogen fuel to small hydrogen vehicles in Denmark seems to be the ideal solution.

However, it has been also documented that autonomous low-pressure on-site HRSs present a fuel cost which is not significantly higher than an offsite counterpart (e.g. 37 €/kg$H_2$ instead of 30 €/kg$H_2$ for Denmark). When considering this cost aligned to the hydrogen demand of small hydrogen vehicles with low-pressure storage (e.g. 15.1 g$H_2$), the difference (i.e. 0.56 € instead of 0.45 €) could become fully acceptable by the consumer.

Hence, in the case of an electricity system that is not based on renewable technologies and RES share in the electricity mix is low, the best HRS option to produce ‘green’ hydrogen for urban small hydrogen mobility is the autonomous on-site HRS able to deliver compressed hydrogen fuel of up to 100 bar of pressure.

# 7. Conclusions and future study

During the last 40 years, the scientific community focusses on the mitigation of the profligate consumption of fossil fuels leading to severe impacts on the environment by suggesting novel technologies towards a sustainable future. Among all carbon intensive activities where new technologies have been implemented, transportation still presents a continuously increasing carbon footprint. New vehicle technologies incorporating electric mobility penetrate the vehicle mix and the auto manufacturing industry aims to find the balance between practicability, sustainability and cost.

One of the technologies that could play a significant role in the decarbonisation of transportation comprises the use of hydrogen in FCEVs. The contribution of this PhD in supporting the transition to 'green' mobility consisted of the assessment of how a hydrogen production system could be integrated in urban transportation to support a fleet of light-duty hydrogen vehicles such as FCEBs and FCESs. The research introduced strategies to perform an in-depth investigation of the subject including literature review, experimental, statistical, and social science analyses. The problem of interest was identified to be multi-dimensional consisting on the one hand a techno-economic aspect and on the other an environmental and social perspective concerning the participation of hydrogen technologies in urban mobility.

In this context, this research was divided in three main parts as described by the stated RQs. The first one focussed on the socio-economic prospects of hydrogen light-duty urban mobility indicating the future hydrogen cost and infrastructure roadmap, and the social perspective regarding hydrogen technologies in transportation. The results indicated that an emerging hydrogen market in road transportation has a large potential to significantly penetrate in the future vehicle mix, as the associated to the market costs are expected to decrease in the next decades with at the same time the social perspective moving towards the right direction. Apparently, from the final customer perspective, the final price of hydrogen fuel could be beneficially lowered by the market dynamic. However, the results presented in section 3.2 showed that the market dynamic in regards to the current 'grey' hydrogen fuel cost is not going to be significantly affected in Denmark. This however, does not reflect to the case of RES derived hydrogen that could push prices to increase in the short term. Thus, one may argue that a future increase of the cost of 'green' hydrogen fuel might impose a different customer's perspective in Denmark, which could be negative towards an increasing trend of the fuel price. Therefore, the investigation of the most financial acceptable solution for the consumers is deemed crucial for the expansion of a 'green' hydrogen market in the transportation sector.

Definitely, there is a long road until hydrogen-based transportation would be fully comparable to the conventional counterpart and the results presented in this dissertation aim to provide a guide to business stakeholders about why and how ‘green’ hydrogen technologies could be adopted as a feasible urban transport alternative.

In this context, the second part of this research examined the potential of an integrated RES-based hydrogen system to the electricity and transportation markets. The research outcome indicated that such a system could be financially viable when participating in both electricity and transportation markets but with low energy round-trip efficiency and high fuel cost delivered to HRSs. Additionally, the investigation showed that the more a hydrogen production unit operates (i.e. high capacity factor) the lower is the cost of the delivered to transportation fuel. Operation of the system only during excess wind energy might introduce high fuel prices when excess wind energy is not always available. However, in that case, hydrogen production would provide major environmental benefits as the $CO_2$ emissions abatement would be significant.

A hydrogen production-storage system participating in the electricity and transportation markets could be a major asset in supporting RES penetration as its inherent operation of storing energy in the form of hydrogen could allow further investments in the RES sector. At the same time, the produced hydrogen could be used in multiple markets maximising the profits and the viability in general of the investment. In contrast, one may argue that likewise, BEV infrastructure could facilitate RES penetration. This could be achieved via the V2G topology, where BEVs are used as a distributed energy storage system to absorb excess RES energy whenever this occurs. However, this is not always the case as unlike to ‘green’ hydrogen production, BEV charging happens mostly during nighttime and thus a thorough demand-supply management along with additional buffer storage systems are required to allow a reliable support to increased RES penetration.

An examined case study in Denmark showed that WH topology is not currently economically acceptable for re-powering applications alone as excess wind energy is limited due to the high penetration of wind power in the electricity system. However, it is expected that with the continuously increasing capacity of wind power, the proposed configuration may allow economically feasible business opportunities for a hydrogen market penetration in the future. On top of that, it has been demonstrated that the participation of a ‘green’ hydrogen production and storage system in the Danish electricity market as a consumer (i.e. load demand/response role) and as hydrogen fuel provider in the transportation market could be an economically viable investment. The fuel cost could be comparable to the high-end of the price range of fossil-fuel derived hydrogen fuel.

The last research section of this project comprised the assessment of which HRS type to support light-duty urban hydrogen mobility would be the most appealing from an investor and consumer perspective. The outcome from four papers documented how the investment and hydrogen fuel cost alters for the different HRS types. The results showed that among the different HRS RES-based SCs, the offsite HRS delivering RES-produced hydrogen from a centralised water electrolysis facility at a low-pressure refuelling process is the best option from the investor and consumer perspective in Denmark. The identification of the best business SC concerning the refuelling infrastructure of light urban hydrogen vehicles with the least carbon footprint is highly depending on the electricity mix of the country, and the HRS's O&M and labour costs. Consequently, it is reasonable that for transportation and electricity markets outside Denmark, the most appealing HRS option documented for Denmark might not be valid. As hydrogen technologies gain more ground in the transportation sector, the continuation of this research could include the application of the developed methodology to other vehicle types such as heavy-duty trucks and trains. Additionally, an overview of what would be the results in more EU countries or other regions would provide an important asset to industry stakeholders aiming at the decarbonisation of the transport sector.

Acknowledging the above, this PhD research provides a detailed methodology for identifying the ideal hydrogen infrastructure for hydrogen urban mobility by securing financial benefits for the investors and the consumers without compromising the environmentally friendliness of hydrogen as an alternative fuel. The main question between most experts in transportation remains:

'*BEVs or FCEVs will play the most significant role towards reaching sustainable transportation?*'

The answer lies on the judge of each individual and it definitely cannot be perceived as an one-dimensional verdict. What could be answered though is that this dissertation's results show that from a financial and social perspective, hydrogen refuelling infrastructure will be comparable to the conventional fuels counterpart in the near future.

# REFERENCES

ACTA, 2014. EL100c/Dryer Hydrogen Generator Manual.

Adolf, J., Balzer, C., Louis, J., Schabla, U., Fischedick, M., Arnold, K., Pastowski, A., Schüwer, D., 2017. Energy of the Future? Sustainable Mobility through Fuel Cells and H2. Shell GmbH, Wuppertal Institute, Hamburg, Germany.

Agnolucci, P., 2007. Hydrogen infrastructure for the transport sector. International Journal of Hydrogen Energy, International Symposium on Solar-Hydrogen-Fuel Cells 2005 32, 3526–3544. https://doi.org/10.1016/j.ijhydene.2007.02.016

Aguado, M., Ayerbe, E., Azcárate, C., Blanco, R., Garde, R., Mallor, F., Rivas, D.M., 2009. Economical assessment of a wind–hydrogen energy system using WindHyGen® software. International Journal of Hydrogen Energy 34, 2845–2854. https://doi.org/10.1016/j.ijhydene.2008.12.098

Ahmadi, P., Kjeang, E., 2015. Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces. International Journal of Hydrogen Energy 40, 12905–12917. https://doi.org/10.1016/j.ijhydene.2015.07.147

Akdağ, S.A., Dinler, A., 2009. A new method to estimate Weibull parameters for wind energy applications. Energy Conversion and Management 50, 1761–1766. https://doi.org/10.1016/j.enconman.2009.03.020

Alazemi, J., Andrews, J., 2015. Automotive hydrogen fuelling stations: An international review. Renewable and Sustainable Energy Reviews 48, 483–499. https://doi.org/10.1016/j.rser.2015.03.085

Al-Baghdadi, M.A.R.S., 2005. Modelling of proton exchange membrane fuel cell performance based on semi-empirical equations. Renewable Energy 30, 1587–1599. https://doi.org/10.1016/j.renene.2004.11.015

Alshehri, F., Suárez, V.G., Rueda Torres, J.L., Perilla, A., van der Meijden, M.A.M.M., 2019. Modelling and evaluation of PEM hydrogen technologies for frequency ancillary services in future multi-energy sustainable power systems. Heliyon 5, e01396. https://doi.org/10.1016/j.heliyon.2019.e01396

Altmann, M., Graesel, C., 1998. The acceptance of hydrogen technologies. Study. Munich University.

Alvarez-Mendoza, F., Bacher, P., Madsen, H., Angeles-Camacho, C., 2017. Stochastic model of wind-fuel cell for a semi-dispatchable power generation. Applied Energy 193, 139–148. https://doi.org/10.1016/j.apenergy.2017.02.033

Amica, G., Arneodo Larochette, P., Gennari, F.C., 2020. Light metal hydride-based hydrogen storage system: Economic assessment in Argentina. International Journal of Hydrogen Energy 45, 18789–18801. https://doi.org/10.1016/j.ijhydene.2020.05.036

Andersson, J., Grönkvist, S., 2019. Large-scale storage of hydrogen. International Journal of Hydrogen Energy 44, 11901–11919. https://doi.org/10.1016/j.ijhydene.2019.03.063

Aneke, M., Wang, M., 2016. Energy storage technologies and real life applications – A state of the art review. Applied Energy 179, 350–377. https://doi.org/10.1016/j.apenergy.2016.06.097

Antoine, B., Goran, K., Neven, D., 2008. Energy scenarios for Malta. International Journal of Hydrogen Energy 33, 4235–4246. https://doi.org/10.1016/j.ijhydene.2008.06.010

Apostolou, D., 2020a. Optimisation of a hydrogen production – storage – re-powering system participating in electricity and transportation markets. A case study for Denmark. Applied Energy 265, 114800. https://doi.org/10.1016/j.apenergy.2020.114800

Apostolou, D., 2020b. Assessing the operation and different refuelling cost scenarios of a fuel cell electric bicycle under low-pressure hydrogen storage. International Journal of Hydrogen Energy 45, 23587-23602. https://doi.org/10.1016/j.ijhydene.2020.06.071

Apostolou, D., 2015. Analytical Simulation of a Combined Electrolysis for Hydrogen Production – H2 Storage (PhD Thesis). Heriot Watt University, Edinburgh, UK.

Apostolou, D., Casero, P., Gil, V., Xydis, G., 2020. Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market. International Journal of Hydrogen Energy 46, 5756–5762. https://doi.org/10.1016/j.ijhydene.2020.11.047

Apostolou, D., Enevoldsen, P., 2019. The past, present and potential of hydrogen as a multifunctional storage application for wind power. Renewable and Sustainable Energy Reviews 112, 917–929. https://doi.org/10.1016/j.rser.2019.06.049

Apostolou, D., Enevoldsen, P., Xydis, G., 2019. Supporting green Urban mobility – The case of a small-scale autonomous hydrogen refuelling station. International Journal of Hydrogen Energy, 9th International Conference on Hydrogen Production (ICH2P-2018) 44, 9675–9689. https://doi.org/10.1016/j.ijhydene.2018.11.197

Apostolou, D., Xydis, G., 2019. A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. Renewable and Sustainable Energy Reviews 113, 109292. https://doi.org/10.1016/j.rser.2019.109292

Asadi, S., Nilashi, M., Samad, S., Abdullah, R., Mahmoud, M., Alkinani, M.H., Yadegaridehkordi, E., 2021. Factors impacting consumers' intention toward adoption of electric vehicles in Malaysia. Journal of Cleaner Production 282, 124474. https://doi.org/10.1016/j.jclepro.2020.124474

Assefa, G., Frostell, B., 2007. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. Technology in Society 29, 63–78. https://doi.org/10.1016/j.techsoc.2006.10.007

Ayodele, T.R., Munda, J.L., 2019. Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.05.077

Aziz, M., Huda, M., 2019. Utilization of electric vehicles for frequency regulation in Danish electrical grid. Energy Procedia, Innovative Solutions for Energy Transitions 158, 3020–3025. https://doi.org/10.1016/j.egypro.2019.01.977

Babarit, A., Gilloteaux, J.-C., Clodic, G., Duchet, M., Simoneau, A., Platzer, M.F., 2018. Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters. International Journal of Hydrogen Energy 43, 7266–7289. https://doi.org/10.1016/j.ijhydene.2018.02.144

Ball, M., Wietschel, M., 2009. The future of hydrogen – opportunities and challenges. International Journal of Hydrogen Energy 34, 615–627. https://doi.org/10.1016/j.ijhydene.2008.11.014

Bank of Greece, 2020. Interest Rates on Bank Deposits and Loans: January 2020 [WWW Document]. URL https://www.bankofgreece.gr/en/news-and-media/press-office/news-list/news?announcement=d4f2be68-9df7-4ec2-85bb-2c6fd4000c65 (accessed 8.25.20).

Bechrakis, D.A., McKeogh, E.J., Gallagher, P.D., 2006. Simulation and operational assessment for a small autonomous wind–hydrogen energy system. Energy Conversion and Management 47, 46–59. https://doi.org/10.1016/j.enconman.2005.03.014

Becker, S., Rodriguez, R.A., Andresen, G.B., Schramm, S., Greiner, M., 2014. Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. Energy 64, 404–418. https://doi.org/10.1016/j.energy.2013.10.010

Bekiaris, E., Tsami, M., Panou, M., 2017. A “Greening Mobility” framework towards sustainability. Transportation Research Procedia 24, 131–136. https://doi.org/10.1016/j.trpro.2017.05.078

Benchouia, N.-E., Elias, H., Derghal, A., Lakhdar, K., Mahmah, B., 2013. Modeling and validation of fuel cell PEMFC. Rev Renew Energy 16, 365–377.

BEREC, 2018. The Weighted Average Cost of Capital (WACC). Body of European regulators for Electronic Communications, Riga, Latvia.

Bernal-Agustín, J.L., Dufo-López, R., 2008. Hourly energy management for grid-connected wind–hydrogen systems. International Journal of Hydrogen Energy 33, 6401–6413. https://doi.org/10.1016/j.ijhydene.2008.08.026

Berning, T., Djilali, N., 2003. Three-dimensional computational analysis of transport phenomena in a PEM fuel cell—a parametric study. Journal of Power Sources 124, 440–452. https://doi.org/10.1016/S0378-7753(03)00816-4

Bertuccioli, L., Chan, A., Hart, D., Lehner, F., Madden, B., Standen, E., 2014. Development of water electrolysis in the European Union. Element Energy, E4tech Sarl, Lausanne Swiss.

Bessarabov, D.G., Wang, H., Li, H., Zhao, N. (Eds.), 2016. PEM electrolysis for hydrogen production: principles and applications. CRC Press, Boca Raton, Florida.

Betalle Memorial Institute, 2017. Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications. Department of Energy (DoE), USA.

Bethlehem, J., 2010. Selection Bias in Web Surveys. International Statistical Review 78, 161–188. https://doi.org/10.1111/j.1751-5823.2010.00112.x

Bhandari, R., Trudewind, C.A., Zapp, P., 2014. Life cycle assessment of hydrogen production via electrolysis – a review. Journal of Cleaner Production, Special Volume: Making Progress Towards More Sustainable Societies through Lean and Green Initiatives 85, 151–163. https://doi.org/10.1016/j.jclepro.2013.07.048

Bhogilla, S.S., Ito, H., Segawa, T., Kato, A., Nakano, A., 2017. Experimental study on laboratory scale Totalized Hydrogen Energy Utilization System using wind power data. International Journal of Hydrogen Energy, Special Issue on The 21st World Hydrogen Energy Conference (WHEC

2016), 13-16 June 2016, Zaragoza, Spain 42, 13827–13838. https://doi.org/10.1016/j.ijhydene.2016.12.125

Bicer, Y., Dincer, I., 2017. Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. International Journal of Hydrogen Energy, The 7th International Conference on Hydrogen Production (ICH2P-2016), 8-11 May 2016, Hangzhou, China 42, 3767–3777. https://doi.org/10.1016/j.ijhydene.2016.07.252

Bishop, J.D.K., Doucette, R.T., Robinson, D., Mills, B., McCulloch, M.D., 2011. Investigating the technical, economic and environmental performance of electric vehicles in the real-world: A case study using electric scooters. Journal of Power Sources 196, 10094–10104. https://doi.org/10.1016/j.jpowsour.2011.08.021

Boden, T., Andres, R., Marland, G., 2017. Global, Regional, and National Fossil-Fuel CO2 Emissions (1751 - 2014) (V. 2017).

Bögel, P., Oltra, C., Sala, R., Lores, M., Upham, P., Dütschke, E., Schneider, U., Wiemann, P., 2018. The role of attitudes in technology acceptance management: Reflections on the case of hydrogen fuel cells in Europe. Journal of Cleaner Production 188, 125–135. https://doi.org/10.1016/j.jclepro.2018.03.266

Bonhoff, K., 2016. Supporting market ramp-up of hydrogen and fuel cell technologies. WHEC 2016, Zaragosa, Spain.

Bosch GmbH, 2019. Charger: the eBike charging device for a quick energy burst [WWW Document]. Bosch eBike Systems. URL https://www.bosch-ebike.com/en/products/charger/ (accessed 7.23.19).

Bowen, A., Huskey, A., Link, H., Sinclair, K., Forsyth, T., Jager, D., van Dam, J., Smith, J., 2009. Small Wind Turbine Testing Results from the National Renewable Energy Lab. Presented at the American Wind Energy Association WINDPOWER 2009, Chicago, USA.

Braun, A., Rid, W., 2017. Energy consumption of an electric and an internal combustion passenger car. A comparative case study from real world data on the Erfurt circuit in Germany. Transportation Research Procedia, 20th EURO Working Group on Transportation Meeting, EWGT 2017, 4-6 September 2017, Budapest, Hungary 27, 468–475. https://doi.org/10.1016/j.trpro.2017.12.044

Breuer, J.L., Samsun, R.C., Peters, R., Stolten, D., 2020. The impact of diesel vehicles on NOx and PM10 emissions from road transport in urban morphological zones: A case study in North Rhine-Westphalia, Germany. Science of The Total Environment 727, 138583. https://doi.org/10.1016/j.scitotenv.2020.138583

Brey, J., Carazo, A., Brey, R., 2018. Exploring the marketability of fuel cell electric vehicles in terms of infrastructure and hydrogen costs in Spain. Renewable and Sustainable Energy Reviews 82, 2893–2899. https://doi.org/10.1016/j.rser.2017.10.042

Brintbiller, 2020. Brinttankstationer i Danmark [WWW Document]. URL https://brintbiler.dk/tankstationer/ (accessed 2.10.20).

Brooks, K.P., Sprik, S.J., Tamburello, D.A., Thornton, M.J., 2020. Design tool for estimating metal hydride storage system characteristics for light-duty hydrogen fuel cell vehicles. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2020.05.159

Brown, D., 2016a. U.S. and World H2 Production 2014. CryoGas International.

Brown, D., 2016b. Hydrogen Supply and Demand: Past, Present, and Future. gasworld.

Brown, R., Golaszewski, P., Brown, B., 2018. Assessing California's climate policies - Transportation. Legislative Analyst's Office, California, USA.

Brown, T., Schell, L.S., Stephens-Romero, S., Samuelsen, S., 2013. Economic analysis of near-term California hydrogen infrastructure. International Journal of Hydrogen Energy 38, 3846–3857. https://doi.org/10.1016/j.ijhydene.2013.01.125

Brown, T., Schlachtberger, D., Kies, A., Schramm, S., Greiner, M., 2018. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 160, 720–739. https://doi.org/10.1016/j.energy.2018.06.222

Brunet, J., Ponssard, J.-P., 2017. Policies and deployment for Fuel Cell Electric Vehicles an assessment of the Normandy project. International Journal of Hydrogen Energy 42, 4276–4284. https://doi.org/10.1016/j.ijhydene.2016.11.202

Burheim, O.S., 2017. Chapter 8 - Hydrogen for Energy Storage, in: Burheim, O.S. (Ed.), Engineering Energy Storage. Academic Press, pp. 147–192. https://doi.org/10.1016/B978-0-12-814100-7.00008-0

Burmistrz, P., Chmielniak, T., Czepirski, L., Gazda-Grzywacz, M., 2016. Carbon footprint of the hydrogen production process utilizing subbituminous coal and lignite gasification. Journal of Cleaner Production 139, 858–865. https://doi.org/10.1016/j.jclepro.2016.08.112

Cabuzel, T., 2020. CO2 emission performance standards for cars and vans [WWW Document]. Climate Action - European Commission. URL https://ec.europa.eu/clima/policies/transport/vehicles/regulation_en (accessed 8.12.20).

California Fuel Cell Partnership, 2020. Cost to refill [WWW Document]. URL https://cafcp.org/content/cost-refill (accessed 5.16.20).

Campíñez-Romero, S., Colmenar-Santos, A., Pérez-Molina, C., Mur-Pérez, F., 2018. A hydrogen refuelling stations infrastructure deployment for cities supported on fuel cell taxi roll-out. Energy 148, 1018–1031. https://doi.org/10.1016/j.energy.2018.02.009

Cardinali, L., Santomassimo, S., Stefanoni, M., 2002. Design and realization of a 300 W fuel cell generator on an electric bicycle. Journal of Power Sources, Proceedings of the Seventh Grove Fuel Cell Symposium 106, 384–387. https://doi.org/10.1016/S0378-7753(01)01059-X

Carley, S., Siddiki, S., Nicholson-Crotty, S., 2019. Evolution of plug-in electric vehicle demand: Assessing consumer perceptions and intent to purchase over time. Transportation Research Part D: Transport and Environment 70, 94–111. https://doi.org/10.1016/j.trd.2019.04.002

Carr, S., Zhang, F., Liu, F., Du, Z., Maddy, J., 2016. Optimal operation of a hydrogen refuelling station combined with wind power in the electricity market. International Journal of Hydrogen Energy 41, 21057–21066. https://doi.org/10.1016/j.ijhydene.2016.09.073

Carton, J.G., Olabi, A.G., 2010. Wind/hydrogen hybrid systems: Opportunity for Ireland's wind resource to provide consistent sustainable energy supply. Energy, The 3rd International Conference on Sustainable Energy and Environmental Protection, SEEP 2009 35, 4536–4544. https://doi.org/10.1016/j.energy.2010.09.010

Caruth, G., 2013. Demystifying Mixed Methods Research Design: A Review of the Literature. Mevlana International Journal of Education 3, 112–122. https://doi.org/10.13054/mije.13.35.3.2

Chade, D., Miklis, T., Dvorak, D., 2015. Feasibility study of wind-to-hydrogen system for Arctic remote locations – Grimsey island case study. Renewable Energy 76, 204–211. https://doi.org/10.1016/j.renene.2014.11.023

Chang, C.-C., Wu, F.-L., Lai, W.-H., Lai, M.-P., 2016. A cost-benefit analysis of the carbon footprint with hydrogen scooters and electric scooters. International Journal of Hydrogen Energy 41, 13299–13307. https://doi.org/10.1016/j.ijhydene.2016.05.168

Chao, D.C.-H., Van Duijsen, P., Hwang, J.J., Liao, C.-W., 2009. Modeling of a Taiwan fuel cell powered scooter, in: Proc Int Conf Power Electron Drive Syst. pp. 913–919. https://doi.org/10.1109/PEDS.2009.5385788

Chavan, S.L., Talange, D.B., 2017. Modeling and performance evaluation of PEM fuel cell by controlling its input parameters. Energy 138, 437–445. https://doi.org/10.1016/j.energy.2017.07.070

Chen, H., Cong, T.N., Yang, W., Tan, C., Li, Y., Ding, Y., 2009. Progress in electrical energy storage system: A critical review. Progress in Natural Science 19, 291–312. https://doi.org/10.1016/j.pnsc.2008.07.014

Cheng, Y.-H., Chang, Y.-H., Lu, I.J., 2015. Urban transportation energy and carbon dioxide emission reduction strategies. Applied Energy 157, 953–973. https://doi.org/10.1016/j.apenergy.2015.01.126

Child, M., Kemfert, C., Bogdanov, D., Breyer, C., 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renewable Energy 139, 80–101. https://doi.org/10.1016/j.renene.2019.02.077

Climate Action Tracker, 2019. Climate Action Tracker [WWW Document]. China-Country Summary. URL https://climateactiontracker.org/countries/china/ (accessed 6.24.19).

Coalition for Urban Transitions, 2019. Climate Emergency. Urban Opportunity. How national governments can secure economic prosperity and avert climate catastrophe by transforming cities. World Resources Institute (WRI) Ross Center for Sustainable Cities and C40 Cities Climate Leadership Group, London and Washington, DC.

Coffman, M., Bernstein, P., Wee, S., 2017. Electric vehicles revisited: a review of factors that affect adoption. Transport Reviews 37, 79–93. https://doi.org/10.1080/01441647.2016.1217282

Cohen, J.J., Reichl, J., Schmidthaler, M., 2014. Re-focussing research efforts on the public acceptance of energy infrastructure: A critical review. Energy 76, 4–9. https://doi.org/10.1016/j.energy.2013.12.056

Colbertaldo, P., Agustin, S.B., Campanari, S., Brouwer, J., 2019. Impact of hydrogen energy storage on California electric power system: Towards 100% renewable electricity. International Journal of Hydrogen Energy, Special Issue on Power To Gas and Hydrogen applications to energy systems at different scales - Building, District and National level 44, 9558–9576. https://doi.org/10.1016/j.ijhydene.2018.11.062

Colella, W.G., 2000. Market prospects, design features, and performance of a fuel cell-powered scooter. Journal of Power Sources 86, 255–260. https://doi.org/10.1016/S0378-7753(99)00486-3

Conlon, T., Waite, M., Modi, V., 2019. Assessing new transmission and energy storage in achieving increasing renewable generation targets in a regional grid. Applied Energy 250, 1085–1098. https://doi.org/10.1016/j.apenergy.2019.05.066

Cortes, D., Green, B., 2019. eLY4OFF PEM electrolysers for operation with offgrid renewable installations. LCA and cost analysis. Huesca, Spain.

Couper, M.P., 2000. Review: Web Surveys: A Review of Issues and Approaches. The Public Opinion Quarterly 64, 464–494.

Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D.P., Mutel, C.L., 2020. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Applied Energy 269, 115021. https://doi.org/10.1016/j.apenergy.2020.115021

Creswell, J.W., Guetterman, T.C., 2019. Educational research: planning, conducting, and evaluating quantitative and qualitative research.

Creti, A., Kotelnikova, A., Meunier, G., Ponssard, J.-P., 2015. A cost benefit analysis of fuel cell electric vehicles (Research Report). -.

Cui, L., Wang, Y., Chen, W., Wen, W., Han, M.S., 2021. Predicting determinants of consumers' purchase motivation for electric vehicles: An application of Maslow's hierarchy of needs model. Energy Policy 151, 112167. https://doi.org/10.1016/j.enpol.2021.112167

Cycling Embassy of Denmark, 2015. Bicycle Statistics from Denmark.

Daimler, 2018b. GLC F-Cell goes into preproduction: World´s first electric vehicle with fuel-cell and battery powertrain [WWW Document]. URL https://www.daimler.com/innovation/specials/iaa-2017/glc-fcell-2.html

Danish Energy Agency, 2016. Danish climate policies [WWW Document]. Energistyrelsen. URL https://ens.dk/en/our-responsibilities/energy-climate-politics/danish-climate-policies (accessed 9.18.19).

Davids, M.W., Lototskyy, M., Malinowski, M., van Schalkwyk, D., Parsons, A., Pasupathi, S., Swanepoel, D., van Niekerk, T., 2019. Metal hydride hydrogen storage tank for light fuel cell vehicle. International Journal of Hydrogen Energy, Special Issue on The 16th International Symposium on Metal-Hydrogen Systems (MH2018), 28 October -2 November 2018, Guangzhou, China 44, 29263–29272. https://doi.org/10.1016/j.ijhydene.2019.01.227

Day, C., Day, G., 2017. Climate change, fossil fuel prices and depletion: The rationale for a falling export tax. Economic Modelling 63, 153–160. https://doi.org/10.1016/j.econmod.2017.01.006

de Miguel, N., Acosta, B., Baraldi, D., Melideo, R., Ortiz Cebolla, R., Moretto, P., 2016. The role of initial tank temperature on refuelling of on-board hydrogen tanks. International Journal of Hydrogen Energy 41, 8606–8615. https://doi.org/10.1016/j.ijhydene.2016.03.158

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., Villafáfila-Robles, R., 2012. A review of energy storage technologies for wind power applications. Renewable and Sustainable Energy Reviews 16, 2154–2171. https://doi.org/10.1016/j.rser.2012.01.029

Diéguez, P.M., Ursúa, A., Sanchis, P., Sopena, C., Guelbenzu, E., Gandía, L.M., 2008. Thermal performance of a commercial alkaline water electrolyzer: Experimental study and mathematical modeling. International Journal of Hydrogen Energy 33, 7338–7354. https://doi.org/10.1016/j.ijhydene.2008.09.051

Dinse, G., 2001. Akzeptanz von wasserstoffbetriebenen Fahrzeugen: eine Studie über die Verwendung eines neuen und ungewohnten Kraftstoffs, 5. Aufl. ed, ifmo-studien. Inst. für Mobilitätsforschung, Berlin.

Direct Bikes, 2019. Scooters [WWW Document]. URL http://www.scooter.co.uk (accessed 7.24.19).

Doğan Öztürk, E., Lükewille, A., González Ortiz, A., Viana, M., Bartonova, A., Guerreiro, C., Leeuw, F. de, European Environment Agency, 2019. Europe's urban air quality: re-assessing implementation challenges in cities.

DTU Transport, 2015. Transportvaneundersøgelsen. Denmark's Technical University.

Dudenhöffer, K., 2013. Why electric vehicles failed: An experimental study with PLS approach based on the Technology Acceptance Model. J Manag Control 24, 95–124. https://doi.org/10.1007/s00187-013-0174-2

Dutton, A.G., Bleijs, J.A.M., Dienhart, H., Falchetta, M., Hug, W., Prischich, D., Ruddell, A.J., 2000. Experience in the design, sizing, economics, and implementation of autonomous wind-powered hydrogen production systems. International Journal of Hydrogen Energy 25, 705–722. https://doi.org/10.1016/S0360-3199(99)00098-1

EAFO, 2020. Electric vehicles [WWW Document]. European Alternative Fuels Observatory. URL https://www.eafo.eu/vehicles-and-fleet/m1 (accessed 8.12.20).

EAFO, 2019a. Alternative fuel vehicles [WWW Document]. URL http://www.eafo.eu/vehicle-statistics/fcev

EAFO, 2019b. Passenger cars - Number of alternative fuels passenger cars - BEVs [WWW Document]. URL https://www.eafo.eu/vehicles-and-fleet/m1 (accessed 12.5.19).

EAFO, 2019c. Passenger cars - Number of alternative fuels passenger cars - H2 [WWW Document]. URL https://www.eafo.eu/vehicles-and-fleet/m1 (accessed 12.5.19).

EAFO, 2019d. Electric vehicle charging infrastructure [WWW Document]. URL http://www.eafo.eu/electric-vehicle-charging-infrastructure

EC, 2016. 2030 climate & energy framework - 2050 long-term strategy [WWW Document]. Climate Action - European Commission. URL https://ec.europa.eu/clima/policies/strategies/2030_en (accessed 8.12.20).

Eichman, J., Townsend, A., Melaina, M., 2016. Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets. National Renewable Energy Laboratory (NREL), Golden CO, USA.

Emonts, B., Reuß, M., Stenzel, P., Welder, L., Knicker, F., Grube, T., Görner, K., Robinius, M., Stolten, D., 2019. Flexible sector coupling with hydrogen: A climate-friendly fuel supply for road transport. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.03.183

Energinet, 2019. Electricity Balance [WWW Document]. Energi Data Service. URL https://www.energidataservice.dk/en/dataset/electricitybalance (accessed 9.12.19).

Energistyrelsen, 2016. Dansk klimapolitik [WWW Document]. Energistyrelsen. URL https://ens.dk/ansvarsomraader/energi-klimapolitik/fakta-om-dansk-energi-klimapolitik/dansk-klimapolitik (accessed 3.29.19).

Enevoldsen, P., 2018. A socio-technical framework for examining the consequences of deforestation: A case study of wind project development in Northern Europe. Energy Policy 115, 138–147. https://doi.org/10.1016/j.enpol.2018.01.007

Enevoldsen, P., Hou, P., Eichman, J., 2018. Examining the business incentives for investments in coupled wind – storage systems. WindEurope Workshop 2018 - Vilnius, Lithuania.

Enevoldsen, P., Sovacool, B.K., 2016. Integrating power systems for remote island energy supply: Lessons from Mykines, Faroe Islands. Renewable Energy 85, 642–648. https://doi.org/10.1016/j.renene.2015.06.065

Enevoldsen, P., Valentine, S.V., 2016. Do onshore and offshore wind farm development patterns differ? Energy for Sustainable Development 35, 41–51. https://doi.org/10.1016/j.esd.2016.10.002

Engmann, T.S., 2020. More Danes participate in online democracy [WWW Document]. URL https://www.dst.dk/da/Statistik/bagtal/2020/2020-03-11-flere-danskere-deltager-i-online-demokrati (accessed 11.8.20).

EREA, DEA, 2019. Fuel Price Projections for Vietnam. Background to the Vietnam Energy Outlook Report 2019. Denmark.

EU, I.E., 2018. Sustainable urban mobility plans. A Policy brief from the policy learning platform on low-carbon economy.

European Automobile Manufacturers Association, 2018. New Passenger Car Registrations by Alternative Fuel Type in the European Union - 2013, 2014, 2015, 2016, 2017. Belgium.

European Commission, 2020a. Climate strategies & targets [WWW Document]. Climate Action - European Commission. URL https://ec.europa.eu/clima/policies/strategies_en (accessed 9.21.20).

European Commission, 2020b. EU transport in figures: statistical pocketbook 2020.

European Commission, 2019a. A European Green Deal [WWW Document]. European Commission. URL https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed 2.22.21).

European Commission, 2019b. Urban mobility [WWW Document]. Mobility and Transport. URL https://ec.europa.eu/transport/themes/urban/urban_mobility_en (accessed 7.8.19).

European Commission, 2019c. Taxation trends in the European Union: data for the EU Member States, Iceland and Norway.

European Commission, 2016a. 2020 climate & energy package [WWW Document]. URL https://ec.europa.eu/clima/policies/strategies/2020_en

European Commission, 2016b. 2050 low-carbon economy [WWW Document]. URL https://ec.europa.eu/clima/policies/strategies/2050_en

European Commission, Directorate General for Mobility and Transport, 2018. EU transport in figures: statistical pocketbook.

European Commission, Eurostat, 2017. EU transport in figures. 2017.

European Committee for Standardization, 2017. CEN - EN 15194 - Cycles - Electrically power assisted cycles - EPAC Bicycles [WWW Document]. CEN - EN 15194. URL https://standards.globalspec.com/std/10260080/EN%2015194 (accessed 5.27.20).

European Environment Agency, 2020. Greenhouse gas emissions from transport in Europe [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-12 (accessed 9.21.20).

European Environment Agency, 2018. Transport fuel prices and taxes [WWW Document]. URL https://www.eea.europa.eu/data-and-maps/indicators/fuel-prices-and-taxes/assessment-4

European Union, Interreg Europe, 2018. Sustainable urban mobility plans. A Policy brief from the policy learning platform on low-carbon economy.

Eurostat, 2020a. Greenhouse gas emissions by source sector [WWW Document]. URL https://ec.europa.eu/eurostat/web/climate-change/data/database (accessed 8.12.20).

Eurostat, 2020b. Gross domestic product at market prices in EU-27 by country [WWW Document]. URL https://ec.europa.eu/eurostat/databrowser/view/tec00001/default/table?lang=en (accessed 11.17.20).

Eurostat, 2020c. Electricity prices for non-household consumers 20 - 500 MWh 2019 [WWW Document]. URL https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (accessed 8.25.20).

Eurostat, 2019a. Energy Database - Energy statistics, quantities [WWW Document]. URL https://ec.europa.eu/eurostat/web/energy/data/database (accessed 9.10.19).

Eurostat, 2019b. Population [WWW Document]. Database. URL https://ec.europa.eu/eurostat/data/database (accessed 12.6.19).

Eurostat, 2019c. Shares of Renewables [WWW Document]. Energy from renewable energy sources. URL https://ec.europa.eu/eurostat/web/energy/data/shares (accessed 6.25.19).

Eurostat, 2019d. Electricity price statistics for household consumers [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics (accessed 7.23.19).

EV-volumes, 2020. The Electric Vehicle World Sales Database [WWW Document]. URL https://www.ev-volumes.com/ (accessed 2.23.21).

Ezzat, M.F., Dincer, I., 2018. Development, analysis and assessment of fuel cell and photovoltaic powered vehicles. International Journal of Hydrogen Energy 43, 968–978. https://doi.org/10.1016/j.ijhydene.2017.05.065

Faber, J., Fonseca, L.M., 2014. How sample size influences research outcomes. Dental Press J Orthod 19, 27–29. https://doi.org/10.1590/2176-9451.19.4.027-029.ebo

Fang, R., 2019. Life cycle cost assessment of wind power–hydrogen coupled integrated energy system. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.03.192

Fang, R., Liang, Y., 2019. Control strategy of electrolyzer in a wind-hydrogen system considering the constraints of switching times. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.03.033

FCH 2JU, 2019. Hydrogen roadmap Europe: a sustainable pathway for the European energy transition.

Ferrero, D., Gamba, M., Lanzini, A., Santarelli, M., 2016. Power-to-Gas Hydrogen: Techno-economic Assessment of Processes towards a Multi-purpose Energy Carrier. Energy Procedia, ATI 2016 - 71st Conference of the Italian Thermal Machines Engineering Association 101, 50–57. https://doi.org/10.1016/j.egypro.2016.11.007

Fishman, E., Cherry, C., 2015. E-bikes in the Mainstream: Reviewing a Decade of Research. Transport Reviews 36. https://doi.org/10.1080/01441647.2015.1069907

Fowler, M.W., Mann, R.F., Amphlett, J.C., Peppley, B.A., Roberge, P.R., 2002. Incorporation of voltage degradation into a generalised steady state electrochemical model for a PEM fuel cell. Journal of Power Sources, Proceedings of the Seventh Grove Fuel Cell Symposium 106, 274–283. https://doi.org/10.1016/S0378-7753(01)01029-1

Frank, E.D., Elgowainy, A., Khalid, Y.S., Peng, J.-K., Reddi, K., 2019. Refueling-station costs for metal hydride storage tanks on board hydrogen fuel cell vehicles. International Journal of Hydrogen Energy 44, 29849–29861. https://doi.org/10.1016/j.ijhydene.2019.09.206

Frischknecht, R., Messmer, A., Stolz, P., Tuchschmid, M., 2016. mobitool Grundlagenbericht Hintergrund, Methodik & Emissionsfaktoren. https://doi.org/10.13140/RG.2.2.24306.09921

Fuel Cell & Hydrogen Energy Association, 2018. Transportation [WWW Document]. URL http://www.fchea.org/transportation/

Fuel Cell Today, 2018. Fuel Cell History [WWW Document]. URL http://www.fuelcelltoday.com/history#Origins

G. García Clúa, J., Mantz, R.J., De Battista, H., 2011. Evaluation of hydrogen production capabilities of a grid-assisted wind–H2 system. Applied Energy 88, 1857–1863. https://doi.org/10.1016/j.apenergy.2010.11.043

Gandía, L.M., Oroz, R., Ursúa, A., Sanchis, P., Diéguez, P.M., 2007. Renewable Hydrogen Production: Performance of an Alkaline Water Electrolyzer Working under Emulated Wind Conditions. Energy & Fuels 21, 1699–1706. https://doi.org/10.1021/ef060491u

Ge, J., Lei, Y., Xu, Q., Wang, X., 2016. Sectoral roles in greenhouse gas emissions and policy implications for energy utilization and carbon emissions trading: a case study of Beijing, China. SpringerPlus 5, 1286. https://doi.org/10.1186/s40064-016-2982-y

Genç, G., Çelik, M., Serdar Genç, M., 2012. Cost analysis of wind-electrolyzer-fuel cell system for energy demand in Pınarbaşı-Kayseri. International Journal of Hydrogen Energy, 12th CHEC 37, 12158–12166. https://doi.org/10.1016/j.ijhydene.2012.05.058

Ghandehariun, S., Kumar, A., 2016. Life cycle assessment of wind-based hydrogen production in Western Canada. International Journal of Hydrogen Energy 41, 9696–9704. https://doi.org/10.1016/j.ijhydene.2016.04.077

Gielen, D., Simbolotti, G., 2005. Prospects for Hydrogen and Fuel Cells. IEA, Paris, France.

Gillete, J.L., Kolpa, R.L., 2007. Overview of Interstate Hydrogen Pipeline Systems. Argonne National Laboratory, Illinois, USA.

Gim, B., Yoon, W.L., 2012. Analysis of the economy of scale and estimation of the future hydrogen production costs at on-site hydrogen refueling stations in Korea. International Journal of Hydrogen Energy, 2011 International Workshop on Molten Carbonates & Related Topics 37, 19138–19145. https://doi.org/10.1016/j.ijhydene.2012.09.163

Global Petrol Prices, 2019. Gasoline and diesel prices by country [WWW Document]. GlobalPetrpPrices.com. URL https://www.globalpetrolprices.com/ (accessed 7.23.19).

Globisch, J., Dütschke, E., Schleich, J., 2018. Acceptance of electric passenger cars in commercial fleets. Transportation Research Part A: Policy and Practice 116, 122–129. https://doi.org/10.1016/j.tra.2018.06.004

Gökçek, M., 2010. Hydrogen generation from small-scale wind-powered electrolysis system in different power matching modes. International Journal of Hydrogen Energy, Indo-French Workshop on Biohydrogen: from Basic Concepts to Technology 35, 10050–10059. https://doi.org/10.1016/j.ijhydene.2010.07.149

González, A., McKeogh, E., Gallachóir, B.Ó., 2004. The role of hydrogen in high wind energy penetration electricity systems: The Irish case. Renewable Energy 29, 471–489. https://doi.org/10.1016/j.renene.2003.07.006

Greiner, C.J., KorpÅs, M., Holen, A.T., 2007. A Norwegian case study on the production of hydrogen from wind power. International Journal of Hydrogen Energy, EHEC2005 32, 1500–1507. https://doi.org/10.1016/j.ijhydene.2006.10.030

Grote, M., Williams, I., Preston, J., Kemp, S., 2016. Including congestion effects in urban road traffic CO2 emissions modelling: Do Local Government Authorities have the right options? Transportation Research Part D: Transport and Environment 43, 95–106. https://doi.org/10.1016/j.trd.2015.12.010

Grueger, F., Möhrke, F., Robinius, M., Stolten, D., 2017. Early power to gas applications: Reducing wind farm forecast errors and providing secondary control reserve. Applied Energy 192, 551–562. https://doi.org/10.1016/j.apenergy.2016.06.131

Grüger, F., Hoch, O., Hartmann, J., Robinius, M., Stolten, D., 2018. Optimized electrolyzer operation: Employing forecasts of wind energy availability, hydrogen demand, and electricity prices. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2018.07.165

Guandalini, G., Campanari, S., Romano, M.C., 2015. Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment. Applied Energy 147, 117–130. https://doi.org/10.1016/j.apenergy.2015.02.055

Guandalini, G., Campanari, S., Valenti, G., 2016. Comparative assessment and safety issues in state-of-the-art hydrogen production technologies. International Journal of Hydrogen Energy 41, 18901–18920. https://doi.org/10.1016/j.ijhydene.2016.08.015

Guerra, j., Eichman, J., Hodge, B., Kurtz, J., 2018. Cost-Competitive Electrolysis-Based Hydrogen Under Current U.S. Electric Utility Rates.

Guney, M.S., Tepe, Y., 2017. Classification and assessment of energy storage systems. Renewable and Sustainable Energy Reviews 75, 1187–1197. https://doi.org/10.1016/j.rser.2016.11.102

Gurz, M., Baltacioglu, E., Hames, Y., Kaya, K., 2017. The meeting of hydrogen and automotive: A review. International Journal of Hydrogen Energy 42, 23334–23346. https://doi.org/10.1016/j.ijhydene.2017.02.124

Gye, H.-R., Seo, S.-K., Bach, Q.-V., Ha, D., Lee, C.-J., 2019. Quantitative risk assessment of an urban hydrogen refueling station. International Journal of Hydrogen Energy 44, 1288–1298. https://doi.org/10.1016/j.ijhydene.2018.11.035

H2.LIVE, 2020. Hydrogen Stations in Germany & Europe [WWW Document]. H2 Mobility. URL https://h2.live/en (accessed 5.16.20).

H2Tools, 2018. International Hydrogen Fuelling Stations. Pacific Northwest National Laboratory.

Hacatoglu, K., Dincer, I., Rosen, M.A., 2016. Sustainability of a wind-hydrogen energy system: Assessment using a novel index and comparison to a conventional gas-fired system. International Journal of Hydrogen Energy, Special Issue on Progress in Hydrogen Production and Applications (ICH2P-2015), 3-6 May 2015, Oshawa, Ontario, Canada 41, 8376–8385. https://doi.org/10.1016/j.ijhydene.2016.01.135

Hackbarth, A., Madlener, R., 2016. Willingness-to-pay for alternative fuel vehicle characteristics: A stated choice study for Germany. Transportation Research Part A: Policy and Practice 85, 89–111. https://doi.org/10.1016/j.tra.2015.12.005

Hamidu, M., 2017. Deducing of an Automobile Design for an Electric Vehicle (EV): Perspective of Technological Acceptance Model (TAM). International Journal of Transportation Engineering and Technology 3, 39. https://doi.org/10.11648/j.ijtet.20170303.12

Han, G., Kwon, Y., Kim, J.B., Lee, S., Bae, J., Cho, E., Lee, B.J., Cho, S., Park, J., 2020. Development of a high-energy-density portable/mobile hydrogen energy storage system incorporating an electrolyzer, a metal hydride and a fuel cell. Applied Energy 259, 114175. https://doi.org/10.1016/j.apenergy.2019.114175

Hardman, S., Chandan, A., Shiu, E., Steinberger-Wilckens, R., 2016. Consumer attitudes to fuel cell vehicles post trial in the United Kingdom. International Journal of Hydrogen Energy 41, 6171–6179. https://doi.org/10.1016/j.ijhydene.2016.02.067

Hardman, S., Jenn, A., Tal, G., Axsen, J., Beard, G., Daina, N., Figenbaum, E., Jakobsson, N., Jochem, P., Kinnear, N., Plötz, P., Pontes, J., Refa, N., Sprei, F., Turrentine, T., Witkamp, B., 2018. A review of consumer preferences of and interactions with electric vehicle charging infrastructure. Transportation Research Part D: Transport and Environment 62, 508–523. https://doi.org/10.1016/j.trd.2018.04.002

Hardman, S., Shiu, E., Steinberger-Wilckens, R., Turrentine, T., 2017. Barriers to the adoption of fuel cell vehicles: A qualitative investigation into early adopters attitudes. Transportation Research Part A: Policy and Practice 95, 166–182. https://doi.org/10.1016/j.tra.2016.11.012

HEDNO, 2018. Issuance of Power Generation Informative Report for the non Interconnected Islands February 2018 - April 2018.

Hienuki, S., Hirayama, Y., Shibutani, T., Sakamoto, J., Nakayama, J., Miyake, A., 2019. How Knowledge about or Experience with Hydrogen Fueling Stations Improves Their Public Acceptance. Sustainability 11, 6339. https://doi.org/10.3390/su11226339

HOFER Hochdrucktechnik GmbH, 2010. Capacity/power consumption of a MKZ120-15/100-40 hydrogen compressor - Data Manual.

Hosseini, S.E., Wahid, M.A., 2016. Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. Renewable and Sustainable Energy Reviews 57, 850–866. https://doi.org/10.1016/j.rser.2015.12.112

Hou, P., Enevoldsen, P., Eichman, J., Hu, W., Jacobson, M.Z., Chen, Z., 2017. Optimizing investments in coupled offshore wind -electrolytic hydrogen storage systems in Denmark. Journal of Power Sources 359, 186–197. https://doi.org/10.1016/j.jpowsour.2017.05.048

Houmøller, A.P., 2017. Chapter 5 - Scandinavian Experience of Integrating Wind Generation in Electricity Markets, in: Jones, L.E. (Ed.), Renewable Energy Integration (Second Edition). Academic Press, Boston, pp. 55–68. https://doi.org/10.1016/B978-0-12-809592-8.00005-6

Hsieh, I.-Y.L., Green, W.H., 2020. Transition to Electric Vehicles in China: Implications for Total Cost of Ownership and Cost to Society. SAE J. STEEP 1, 13-01-02–0005. https://doi.org/10.4271/13-01-02-0005

Hu, X., Zou, C., Tang, X., Liu, T., Hu, L., 2020. Cost-Optimal Energy Management of Hybrid Electric Vehicles Using Fuel Cell/Battery Health-Aware Predictive Control. IEEE Transactions on Power Electronics 35, 382–392.

Huang, J., 2018. Outlook on the EU road fuel consumption through 2035. Aramco, Utrecht University.

Huang, Y.W., Kittner, N., Kammen, D.M., 2019. ASEAN grid flexibility: Preparedness for grid integration of renewable energy. Energy Policy 128, 711–726. https://doi.org/10.1016/j.enpol.2019.01.025

Huijts, N.M.A., Molin, E.J.E., Steg, L., 2012. Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. Renewable and Sustainable Energy Reviews 16, 525–531. https://doi.org/10.1016/j.rser.2011.08.018

Hulten, C.R., McCallum, J., Institute, U. (Eds.), 1981. Depreciation, inflation, and the taxation of income from capital. Urban Institute Press, Washington, D.C.

HUMMER Industries, 2018. H17-50KW Wind turbine Generator [WWW Document]. Products. URL http://www.chinahummer.cn/index.php/index/content/165 (accessed 2.13.18).

Hvelplund, F., Østergaard, P.A., Meyer, N.I., 2017. Incentives and barriers for wind power expansion and system integration in Denmark. Energy Policy 107, 573–584. https://doi.org/10.1016/j.enpol.2017.05.009

Hwang, J.J., 2012. Review on development and demonstration of hydrogen fuel cell scooters. Renewable and Sustainable Energy Reviews 16, 3803–3815. https://doi.org/10.1016/j.rser.2012.03.036

Hwang, J.J., Chang, W.R., 2012. Characteristic study on fuel cell/battery hybrid power system on a light electric vehicle. Journal of Power Sources 207, 111–119. https://doi.org/10.1016/j.jpowsour.2012.02.008

Hwang, J.J., Chang, W.R., 2010. Life-cycle analysis of greenhouse gas emission and energy efficiency of hydrogen fuel cell scooters. International Journal of Hydrogen Energy, VIII symposium of the Mexican Hydrogen Society 35, 11947–11956. https://doi.org/10.1016/j.ijhydene.2010.07.148

Hwang, J.J., Wang, D.Y., Shih, N.C., 2005. Development of a lightweight fuel cell vehicle. Journal of Power Sources 141, 108–115. https://doi.org/10.1016/j.jpowsour.2004.08.056

Hwang, J.J., Wang, D.Y., Shih, N.C., Lai, D.Y., Chen, C.K., 2004. Development of fuel-cell-powered electric bicycle. Journal of Power Sources 133, 223–228. https://doi.org/10.1016/j.jpowsour.2004.02.004

Hydrogen Council, 2017a. Hydrogen Scaling Up. A sustainable pathway for the global energy transition. McKinsey & Company.

Hydrogen Council, 2017b. How hydrogen empowers the energy transition. Hydrogen Europe.

Hydrogen Energy Navi, 2019. Hydrogen Energy Vision [WWW Document]. URL http://hydrogen-navi.jp/en/significance/index.html (accessed 5.7.19).

Hydro-Pac inc., 2020. LX-Series$^{TM}$ Hydrogen Gas Compressors, Two-Stage Units from Hydro-Pac [WWW Document]. URL https://www.thomasnet.com/catalogs/productline/156152-8204-1006/hydro-pac/lx-series-8482-hydrogen-gas-compressors-two-stage-units/ (accessed 5.1.20).

IEA, 2020a. Tracking Transport [WWW Document]. IEA. URL https://www.iea.org/reports/tracking-transport-2020 (accessed 10.31.20).

IEA, 2020b. Key energy statistics - Total $CO_2$ emissions [WWW Document]. Data and Statistics. URL https://www.iea.org/data-and-statistics?country=WORLD&fuel=CO2%20emissions&indicator=TotCO2 (accessed 10.31.20).

IEA, 2020c. Global $CO_2$ emissions in 2019 [WWW Document]. IEA. URL https://www.iea.org/articles/global-co2-emissions-in-2019 (accessed 2.20.20).

IEA, 2019a. Survey on the Number of Fuel Cell Vehicles, Hydrogen Refueling Stations and Targets. AFC TCP.

IEA, 2019b. More efforts needed [WWW Document]. URL https://www.iea.org/tcep/energyintegration/hydrogen/

IEA, 2019c. The Future of Hydrogen. Seizing today's opportunities (Prepared for the G20, Japan). International Energy Agency, France.

IEA, 2017a. $CO_2$ emissions from fuel combustion highlights. Paris, France.

IEA, 2017b. Global EV Outlook 2017. Two Million and Counting. France.

IEA, 2015. Technology Roadmap. Hydrogen and Fuel Cells. Paris, France.

IEA, 2012. Technology Roadmap: Fuel Economy of Road Vehicles. International Energy Agency, France.

Information Trends, 2018. Hydrogen Fuel Cell Vehicles: A Global Analysis [WWW Document]. Information Trends. URL http://informationtrends.net/pr-fcev-3q.html (accessed 2.1.18).

Iordache, M., Schitea, D., Iordache, I., 2017. Hydrogen refuelling station infrastructure roll-up, an indicative assessment of the commercial viability and profitability in the Member States of

Europe Union. International Journal of Hydrogen Energy 42, 29629–29647. https://doi.org/10.1016/j.ijhydene.2017.09.146

IPPC, Edenhofer, O. (Eds.), 2014. Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

Iqbal, M.T., 2003. Simulation of a small wind fuel cell hybrid energy system. Renewable Energy 28, 511–522. https://doi.org/10.1016/S0960-1481(02)00070-8

IRENA, 2018. Hydrogen from Renewable Power – Technology Outlook for the Energy Transition. International Renewable Energy Agency.

IRENA, European Commission, 2018. Renewable Energy Prospects for the European Union. International Renewable Energy Agency (IRENA), Abu Dhabi.

Iribarren, D., Martín-Gamboa, M., Manzano, J., Dufour, J., 2016. Assessing the social acceptance of hydrogen for transportation in Spain: An unintentional focus on target population for a potential hydrogen economy. International Journal of Hydrogen Energy 41, 5203–5208. https://doi.org/10.1016/j.ijhydene.2016.01.139

Isenstadt, A., Lutsey, N., 2017. Developing hydrogen fueling infrastructure for fuel cell vehicles: A status update. International Council on Clean Transportation (ICCT).

Ishaq, H., Dincer, I., Naterer, G.F., 2018. Performance investigation of an integrated wind energy system for co-generation of power and hydrogen. International Journal of Hydrogen Energy 43, 9153–9164. https://doi.org/10.1016/j.ijhydene.2018.03.139

Itaoka, K., Saito, A., Sasaki, K., 2017. Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. International Journal of Hydrogen Energy, Special issue on The 6th International Conference on Hydrogen Safety (ICHS 2015), 19-21 October 2015, Yokohama, Japan 42, 7290–7296. https://doi.org/10.1016/j.ijhydene.2016.10.123

Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A.F., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., Erwin, J.R., Fobi, S.N., Goldstrom, O.K., Hennessy, E.M., Liu, J., Lo, J., Meyer, C.B., Morris, S.B., Moy, K.R., O'Neill, P.L., Petkov, I., Redfern, S., Schucker, R., Sontag, M.A., Wang, J., Weiner, E., Yachanin, A.S., 2017. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule 1, 108–121. https://doi.org/10.1016/j.joule.2017.07.005

Jacobson, M.Z., Delucchi, M.A., Cameron, M.A., Mathiesen, B.V., 2018. Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes. Renewable Energy 123, 236–248. https://doi.org/10.1016/j.renene.2018.02.009

James, B.D., 2019. 2019 DOE hydrogen and fuel cells program review presentation - Fuel cell systems analysis.

Jonker, J., Pennink, B., 2009. The Essence of Research Methodology: A Concise Guide for Master and PhD Students in Management Science. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-71659-4

Kaldellis, J.K., Apostolou, D., 2017. Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart. Renewable Energy 108, 72–84. https://doi.org/10.1016/j.renene.2017.02.039

Kaldellis, J.K., Kavadias, K., Zafirakis, D., 2015. The role of hydrogen-based energy storage in the support of large-scale wind energy integration in island grids. International Journal of Sustainable Energy 34, 188–201. https://doi.org/10.1080/14786451.2013.846342

Katikaneni, S.P., Al-Muhaish, F., Harale, A., Pham, T.V., 2014. On-site hydrogen production from transportation fuels: An overview and techno-economic assessment. International Journal of Hydrogen Energy 39, 4331–4350. https://doi.org/10.1016/j.ijhydene.2013.12.172

Kavadias, K.A., Apostolou, D., Kaldellis, J.K., 2018. Modelling and optimisation of a hydrogen-based energy storage system in an autonomous electrical network. Applied Energy 227, 574–586. https://doi.org/10.1016/j.apenergy.2017.08.050

Keles, D., Wietschel, M., Möst, D., Rentz, O., 2008. Market penetration of fuel cell vehicles – Analysis based on agent behaviour. International Journal of Hydrogen Energy 33, 4444–4455. https://doi.org/10.1016/j.ijhydene.2008.04.061

Khan, M., 2019. Post-stratification Weighting Adjustment Technique for Reducing Bias in Volunteer Panel Web Surveys.

Khan, M.J., Iqbal, M.T., 2009. Analysis of a small wind-hydrogen stand-alone hybrid energy system. Applied Energy 86, 2429–2442. https://doi.org/10.1016/j.apenergy.2008.10.024

Kheirandish, A., Kazemi, M.S., Dahari, M., 2014. Dynamic performance assessment of the efficiency of fuel cell-powered bicycle: An experimental approach. International Journal of Hydrogen Energy 39, 13276–13284. https://doi.org/10.1016/j.ijhydene.2014.06.138

Khosravi, A., Koury, R.N.N., Machado, L., Pabon, J.J.G., 2018. Energy, exergy and economic analysis of a hybrid renewable energy with hydrogen storage system. Energy 148, 1087–1102. https://doi.org/10.1016/j.energy.2018.02.008

Kilde, M.D., Arroyo, P.G., Gertsen, A.S., Mikkelsen, K.V., Nielsen, M.B., 2018. Molecular solar thermal systems – control of light harvesting and energy storage by protonation/deprotonation. RSC Advances 8, 6356–6364. https://doi.org/10.1039/C7RA13762A

Kim, I., Kim, J., Lee, J., 2020. Dynamic analysis of well-to-wheel electric and hydrogen vehicles greenhouse gas emissions: Focusing on consumer preferences and power mix changes in South Korea. Applied Energy 260, 114281. https://doi.org/10.1016/j.apenergy.2019.114281

Kim, J.-H., Kim, H.-J., Yoo, S.-H., 2019. Willingness to pay for fuel-cell electric vehicles in South Korea. Energy 174, 497–502. https://doi.org/10.1016/j.energy.2019.02.185

Kim, M., Kim, J., 2017. An integrated decision support model for design and operation of a wind-based hydrogen supply system. International Journal of Hydrogen Energy 42, 3899–3915. https://doi.org/10.1016/j.ijhydene.2016.10.129

Köhler, J., Wietschel, M., Whitmarsh, L., Keles, D., Schade, W., 2010. Infrastructure investment for a transition to hydrogen automobiles. Technological Forecasting and Social Change, Issue includes a Special Section on “Infrastructures and Transitions” 77, 1237–1248. https://doi.org/10.1016/j.techfore.2010.03.010

Kolbe, K., 2019. Mitigating urban heat island effect and carbon dioxide emissions through different mobility concepts: Comparison of conventional vehicles with electric vehicles, hydrogen vehicles and public transportation. Transport Policy 80, 1–11. https://doi.org/10.1016/j.tranpol.2019.05.007

Kölbig, M., Bürger, I., Linder, M., 2019. Characterization of metal hydrides for thermal applications in vehicles below 0 °C. International Journal of Hydrogen Energy 44, 4878–4888. https://doi.org/10.1016/j.ijhydene.2018.12.116

Kong, N., 2018. Exploring Electric Vehicle Battery Charging Efficiency. UCDAVIS Institute of Transportation Studies, National Centre for Sustainable Transportation.

Kopp, M., Coleman, D., Stiller, C., Scheffer, K., Aichinger, J., Scheppat, B., 2017. Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis. International Journal of Hydrogen Energy, Special Issue on The 21st World Hydrogen Energy Conference (WHEC 2016), 13-16 June 2016, Zaragoza, Spain 42, 13311–13320. https://doi.org/10.1016/j.ijhydene.2016.12.145

Koroneos, C., Dompros, A., Roumbas, G., Moussiopoulos, N., 2004. Life cycle assessment of hydrogen fuel production processes. International Journal of Hydrogen Energy 29, 1443–1450. https://doi.org/10.1016/j.ijhydene.2004.01.016

Kourkoumpas, D.-S., Benekos, G., Nikolopoulos, N., Karellas, S., Grammelis, P., Kakaras, E., 2018. A review of key environmental and energy performance indicators for the case of renewable energy systems when integrated with storage solutions. Applied Energy 231, 380–398. https://doi.org/10.1016/j.apenergy.2018.09.043

Kovač, A., Paranos, M., 2019. Design of a solar hydrogen refuelling station following the development of the first Croatian fuel cell powered bicycle to boost hydrogen urban mobility. International Journal of Hydrogen Energy, 9th International Conference on Hydrogen Production (ICH2P-2018) 44, 10014–10022. https://doi.org/10.1016/j.ijhydene.2018.11.204

Krause, J., Thiel, C., Tsokolis, D., Samaras, Z., Rota, C., Ward, A., Prenninger, P., Coosemans, T., Neugebauer, S., Verhoeve, W., 2020. EU road vehicle energy consumption and CO2 emissions by 2050 – Expert-based scenarios. Energy Policy 138, 111224. https://doi.org/10.1016/j.enpol.2019.111224

Kuckshinrichs, W., Ketelaer, T., Koj, J.C., 2016. Economic analysis of improved alkaline water electrolysis. Forschungszentrum Jülich, Institute of Energy and Climate Research, Jülich, Germany.

Kurtz, J., Sprik, S., Saur, G., Onorato, S., 2019. Fuel Cell Electric Vehicle Driving and Fueling Behavior (No. NREL/TP-5400-73010). NREL, Golden, CO, USA.

Laurencelle, F., Chahine, R., Hamelin, J., Agbossou, K., Fournier, M., Bose, T., Laperrière, A., 2001. Characterization of a Ballard MK5-E Proton Exchange Membrane Fuel Cell Stack. Fuel Cells 1, 66–71. https://doi.org/10.1002/1615-6854(200105)1:13.3.CO;2-V

Law, K., Rosenfeld, J., Han, V., Chan, M., Chiang, H., Leonard, J., 2013. U.S. Department of Energy Hydrogen Storage Cost Analysis. TIAX LLC, US Department of Energy, California, USA.

Lazard, 2017. Lazard’s Levelized Cost of Energy Analysis-Version 11.0.

Le Duigou, A., Quéméré, M.-M., Marion, P., Menanteau, P., Decarre, S., Sinegre, L., Nadau, L., Rastetter, A., Cuni, A., Mulard, P., Antoine, L., Alleau, T., 2013. Hydrogen pathways in France: Results of the HyFrance3 Project. Energy Policy 62, 1562–1569. https://doi.org/10.1016/j.enpol.2013.06.094

Li, M., Zhang, X., Li, G., 2016. A comparative assessment of battery and fuel cell electric vehicles using a well-to-wheel analysis. Energy 94, 693–704. https://doi.org/10.1016/j.energy.2015.11.023

Li, X., Yu, B., 2019. Peaking CO2 emissions for China’s urban passenger transport sector. Energy Policy 133, 110913. https://doi.org/10.1016/j.enpol.2019.110913

Li, Z., Gao, D., Chang, L., Liu, P., Pistikopoulos, E.N., 2008. Hydrogen infrastructure design and optimization: A case study of China. International Journal of Hydrogen Energy 33, 5275–5286. https://doi.org/10.1016/j.ijhydene.2008.06.076

Lieutenant, K., Borissova, A., 2020. A landscape of hydride compounds for off-board refilling of transport vehicles. International Journal of Hydrogen Energy 45, 2954–2966. https://doi.org/10.1016/j.ijhydene.2019.09.173

Lindboe, H., Werling, J., Dupont, N., Hethey, J., 2015. Integration of wind power. Viking Link and other initiatives for integration of wind power. Ea Energy Analyses a/s, Energinet, Copenhagen, Denmark.

Linnemann, J., Steinberger-Wilckens, R., 2007. Realistic costs of wind-hydrogen vehicle fuel production. International Journal of Hydrogen Energy, EHEC2005 32, 1492–1499. https://doi.org/10.1016/j.ijhydene.2006.10.029

Lipman, T.E., Elke, M., Lidicker, J., 2018. Hydrogen fuel cell electric vehicle performance and user-response assessment: Results of an extended driver study. International Journal of Hydrogen Energy 43, 12442–12454. https://doi.org/10.1016/j.ijhydene.2018.04.172

Liu, X., Reddi, K., Elgowainy, A., Lohse-Busch, H., Wang, M., Rustagi, N., 2020. Comparison of well-to-wheels energy use and emissions of a hydrogen fuel cell electric vehicle relative to a conventional gasoline-powered internal combustion engine vehicle. International Journal of Hydrogen Energy 45, 972–983. https://doi.org/10.1016/j.ijhydene.2019.10.192

Liu, X., Zhang, S., Dong, J., Xu, X., 2016. A Short-term Analysis of Hydrogen Demand and Refueling Station Cost in Shenzhen China. Energy Procedia, Clean Energy for Clean City: CUE 2016--Applied Energy Symposium and Forum: Low-Carbon Cities and Urban Energy Systems 104, 317–322. https://doi.org/10.1016/j.egypro.2016.12.054

Lokaleportalen, 2020. Commercial real estate for lease [WWW Document]. URL https://www.lokaleportalen.dk/en/erhvervslokaler?estate_types=4;1;22&area_from=200&area_to=200 (accessed 8.25.20).

Loosveldt, G., Sonck, N., 2008. An evaluation of the weighting procedures for an online access panel survey. Survey Research Methods 2, 93–105. https://doi.org/10.18148/srm/2008.v2i2.82

Lototskyy, M., Tolj, I., Klochko, Y., Davids, M.W., Swanepoel, D., Linkov, V., 2020. Metal hydride hydrogen storage tank for fuel cell utility vehicles. International Journal of Hydrogen Energy, Special Issue from the 3rd International Symposium on Materials for Energy Storage and

Conversion, 10-12.09.2018, Belgrade, Serbia 45, 7958–7967. https://doi.org/10.1016/j.ijhydene.2019.04.124

Lototskyy, M.V., Davids, M.W., Tolj, I., Klochko, Y.V., Sekhar, B.S., Chidziva, S., Smith, F., Swanepoel, D., Pollet, B.G., 2015. Metal hydride systems for hydrogen storage and supply for stationary and automotive low temperature PEM fuel cell power modules. International Journal of Hydrogen Energy 40, 11491–11497. https://doi.org/10.1016/j.ijhydene.2015.01.095

Lototskyy, M.V., Tolj, I., Davids, M.W., Klochko, Y.V., Parsons, A., Swanepoel, D., Ehlers, R., Louw, G., van der Westhuizen, B., Smith, F., Pollet, B.G., Sita, C., Linkov, V., 2016a. Metal hydride hydrogen storage and supply systems for electric forklift with low-temperature proton exchange membrane fuel cell power module. International Journal of Hydrogen Energy 41, 13831–13842. https://doi.org/10.1016/j.ijhydene.2016.01.148

Lototskyy, M.V., Tolj, I., Parsons, A., Smith, F., Sita, C., Linkov, V., 2016b. Performance of electric forklift with low-temperature polymer exchange membrane fuel cell power module and metal hydride hydrogen storage extension tank. Journal of Power Sources 316, 239–250. https://doi.org/10.1016/j.jpowsour.2016.03.058

Lototskyy, M.V., Tolj, I., Pickering, L., Sita, C., Barbir, F., Yartys, V., 2017. The use of metal hydrides in fuel cell applications. Progress in Natural Science: Materials International, SI-HYDROGEN STORAGE MATERIALS 27, 3–20. https://doi.org/10.1016/j.pnsc.2017.01.008

Ludwig-Bölkow-Systemtechnik, 2017. Hydrogen refuelling Stations 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017.

Lund, T., 2012. Combining Qualitative and Quantitative Approaches: Some Arguments for Mixed Methods Research. Scandinavian Journal of Educational Research 56, 155–165. https://doi.org/10.1080/00313831.2011.568674

Luo, X., Wang, J., Dooner, M., Clarke, J., 2015. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy 137, 511–536. https://doi.org/10.1016/j.apenergy.2014.09.081

Lyseng, B., Niet, T., English, J., Keller, V., Palmer-Wilson, K., Robertson, B., Rowe, A., Wild, P., 2018. System-level power-to-gas energy storage for high penetrations of variable renewables. International Journal of Hydrogen Energy 43, 1966–1979. https://doi.org/10.1016/j.ijhydene.2017.11.162

Maack, M., 2005. Report on social aspects of ECTOS - Hydrogen bus trial in Reykjavik.

Magueta, D., Madaleno, M., Ferreira Dias, M., Meireles, M., 2018. New cars and emissions: Effects of policies, macroeconomic impacts and cities characteristics in Portugal. Journal of Cleaner Production 181, 178–191. https://doi.org/10.1016/j.jclepro.2017.11.243

Marmiroli, B., Venditti, M., Dotelli, G., Spessa, E., 2020. The transport of goods in the urban environment: A comparative life cycle assessment of electric, compressed natural gas and diesel light-duty vehicles. Applied Energy 260, 114236. https://doi.org/10.1016/j.apenergy.2019.114236

Martin, E., Shaheen, S.A., Lipman, T.E., Lidicker, J.R., 2009. Behavioral response to hydrogen fuel cell vehicles and refueling: Results of California drive clinics. International Journal of Hydrogen Energy 34, 8670–8680. https://doi.org/10.1016/j.ijhydene.2009.07.098

Masnadi, M.S., Grace, J.R., Bi, X.T., Lim, C.J., Ellis, N., 2015. From fossil fuels towards renewables: Inhibitory and catalytic effects on carbon thermochemical conversion during co-gasification of biomass with fossil fuels. Applied Energy 140, 196–209. https://doi.org/10.1016/j.apenergy.2014.12.006

Mathur, J., Agarwal, N., Swaroop, R., Shah, N., 2008. Economics of producing hydrogen as transportation fuel using offshore wind energy systems. Energy Policy 36, 1212–1222. https://doi.org/10.1016/j.enpol.2007.11.031

Mayer, T., Semmel, M., Guerrero Morales, M.A., Schmidt, K.M., Bauer, A., Wind, J., 2019. Techno-economic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen. International Journal of Hydrogen Energy 44, 25809–25833. https://doi.org/10.1016/j.ijhydene.2019.08.051

Mayyas, A., 2015. Insights from Hydrogen Refueling Station Manufacturing Competitiveness Analysis.

Mayyas, A., Mann, M., 2016. Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations.

Mazzucco, A., Dornheim, M., Sloth, M., Jensen, T.R., Jensen, J.O., Rokni, M., 2014. Bed geometries, fueling strategies and optimization of heat exchanger designs in metal hydride storage systems for automotive applications: A review. International Journal of Hydrogen Energy 39, 17054–17074. https://doi.org/10.1016/j.ijhydene.2014.08.047

McKinney, J., Bond, E., Crowell, M., Odufuwa, E., 2015. Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California. California Energy Commission, California, USA.

McKinsey & Co, 2010. A portfolio of power-trains for Europe: a fact-based analysis.

Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S., Ulgiati, S., 2018. Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. Environments 5. https://doi.org/10.3390/environments5020024

Mehrpooya, M., Bahnamiri, F.K., Moosavian, S.M.A., 2019. Energy analysis and economic evaluation of a new developed integrated process configuration to produce power, hydrogen, and heat. Journal of Cleaner Production 239, 118042. https://doi.org/10.1016/j.jclepro.2019.118042

Mehta, C., Patel, N., 2012. IBM SPSS Exact Tests.

Melaina, M., Penev, M., 2013. Hydrogen Station Cost Estimates. Comparing Hydrogen Station Cost Calculator Results with other Recent Estimates. National Renewable Laboratory (NREL), Denver, USA.

Melchior, E., Mailund, A., 2018. Doing Business in Denmark. Revitax A/S, Copenhagen, Denmark.

Mellino, S., Petrillo, A., Cigolotti, V., Autorino, C., Jannelli, E., Ulgiati, S., 2017. A Life Cycle Assessment of lithium battery and hydrogen-FC powered electric bicycles: Searching for cleaner solutions to urban mobility. International Journal of Hydrogen Energy, The 6th

European Fuel Cell Technology & Applications Piero Lunghi Conference & Exhibition (EFC15), 16-18 December 2015, Naples, Italy 42, 1830–1840. https://doi.org/10.1016/j.ijhydene.2016.10.146

Mendecka, B., Lombardi, L., 2019. Life cycle environmental impacts of wind energy technologies: A review of simplified models and harmonization of the results. Renewable and Sustainable Energy Reviews 111, 462–480. https://doi.org/10.1016/j.rser.2019.05.019

Messaoudi, D., Settou, N., Negrou, B., Rahmouni, S., Settou, B., Mayou, I., 2019. Site selection methodology for the wind-powered hydrogen refueling station based on AHP-GIS in Adrar, Algeria. Energy Procedia, Emerging and Renewable Energy: Generation and Automation 162, 67–76. https://doi.org/10.1016/j.egypro.2019.04.008

Micena, R.P., Llerena-Pizarro, O.R., de Souza, T.M., Silveira, J.L., 2020. Solar-powered Hydrogen Refueling Stations: A techno-economic analysis. International Journal of Hydrogen Energy 45, 2308–2318. https://doi.org/10.1016/j.ijhydene.2019.11.092

Michalski, J., Bunger, U., Stiller, C., 2011. Business analysis of the hydrogen refueling station infrastructure and the role of the pricing system. International Journal of Hydrogen Energy 36, 8152–8157. https://doi.org/10.1016/j.ijhydene.2011.01.097

Millo, F., Caputo, S., Piu, A., 2016. Analysis of a HT-PEMFC range extender for a light duty full electric vehicle (LD-FEV). International Journal of Hydrogen Energy, Special Issue: Hydrogen and Fuel Cell Developments: A special issue on the 8th International Conference on Sustainable Energy and Environmental Protection (SEEP 2015), 11–14 August 2015, Paisley, Scotland, UK 41, 16489–16498. https://doi.org/10.1016/j.ijhydene.2016.04.120

Minutillo, M., Forcina, A., Jannelli, N., Lubrano Lavadera, A., 2018. Assessment of a sustainable energy chain designed for promoting the hydrogen mobility by means of fuel-cell powered bicycles. Energy 153, 200–210. https://doi.org/10.1016/j.energy.2018.04.014

Mirzaei, M.A., Sadeghi Yazdankhah, A., Mohammadi-Ivatloo, B., 2019. Stochastic security-constrained operation of wind and hydrogen energy storage systems integrated with price-based demand response. International Journal of Hydrogen Energy, A Special Issue based on the papers selected from The 14th International Conference on Energy Storage (EnerStock 2018) 44, 14217–14227. https://doi.org/10.1016/j.ijhydene.2018.12.054

Mohammadi, A., Mehrpooya, M., 2018. A comprehensive review on coupling different types of electrolyzer to renewable energy sources. Energy 158, 632–655. https://doi.org/10.1016/j.energy.2018.06.073

Morrison, G., Stevens, J., Joseck, F., 2018. Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles. Transportation Research Part C: Emerging Technologies 87, 183–196. https://doi.org/10.1016/j.trc.2018.01.005

Moula, Md.M.E., Nyári, J., Bartel, A., 2017. Public acceptance of biofuels in the transport sector in Finland. International Journal of Sustainable Built Environment 6, 434–441. https://doi.org/10.1016/j.ijsbe.2017.07.008

My LPG, 2020. Chart of fuel prices in Denmark - myLPG.eu [WWW Document]. Chart of fuel prices in Denmark. URL https://www.mylpg.eu/stations/denmark/prices/ (accessed 11.14.20).

Nagasawa, K., Davidson, F.T., Lloyd, A.C., Webber, M.E., 2019. Impacts of renewable hydrogen production from wind energy in electricity markets on potential hydrogen demand for light-duty vehicles. Applied Energy 235, 1001–1016. https://doi.org/10.1016/j.apenergy.2018.10.067

Nasri, M., Dickinson, D., 2014. Thermal management of fuel cell-driven vehicles using HT-PEM and hydrogen storage, in: 2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER). Presented at the 2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER), pp. 1–6. https://doi.org/10.1109/EVER.2014.6844107

National Bank - Statbank, 2020. Loans up to and including 7.5 million DKK to non-financial corporations-Annualised agreed rate - 06/2020 [WWW Document]. Banking and mortgage lending. URL https://nationalbanken.statbank.dk/statbank5a/default.asp?w=1843

NEL ASA, 2019. Product Specifications [WWW Document]. URL https://nelhydrogen.com/products/ (accessed 7.29.19).

NEL ASA, 2018. Expands H2Station® product range with new compressor and increased fueling capacity [WWW Document]. URL http://nelhydrogen.com/news/expands-h2station-product-range-with-new-compressor-and-increased-fueling-capacity/

Nie, J., Li, Z., Kong, X., Li, D., 2017. Analysis and Comparison Study on Different HFC Refrigerants for Space Heating Air Source Heat Pump in Rural Residential Buildings of North China. Procedia Engineering 205, 1201–1206. https://doi.org/10.1016/j.proeng.2017.10.354

Nie, X., Wei, X., Xia, Q., Zhou, M., 2020. Customers' purchase intention for hydrogen vehicle and industrial agglomeration: Evidence from Jiangsu Province, China. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2020.10.055

Niehaves, B., Gorbacheva, E., Plattfaut, R., 2012. Social Aspects in Technology Acceptance: Theory Integration and Development, in: 2014 47th Hawaii International Conference on System Sciences. IEEE Computer Society, Los Alamitos, CA, USA, pp. 3149–3158. https://doi.org/10.1109/HICSS.2012.532

Nikolaidis, P., Poullikkas, A., 2017. A comparative overview of hydrogen production processes. Renewable and Sustainable Energy Reviews 67, 597–611. https://doi.org/10.1016/j.rser.2016.09.044

Nistor, S., Dave, S., Fan, Z., Sooriyabandara, M., 2016. Technical and economic analysis of hydrogen refuelling. Applied Energy 167, 211–220. https://doi.org/10.1016/j.apenergy.2015.10.094

O'Dell, J., 2019b. Nikola Details Ambitious Plan for Hydrogen and Service Network [WWW Document]. URL https://www.trucks.com/2019/04/22/nikola-ambitious-plan-hydrogen-service-network/

OECD, 2019a. Greenhouse gas emissions [WWW Document]. OECD.Stat. URL https://stats.oecd.org/Index.aspx?DataSetCode=AIR_GHG (accessed 6.24.19).

OECD, 2019b. Average annual wages - Greece [WWW Document]. URL https://stats.oecd.org/Index.aspx?QueryName=426&QueryType=View&Lang=en (accessed 10.17.20).

O'Garra, T., Mourato, S., Garrity, L., Schmidt, P., Beerenwinkel, A., Altmann, M., Hart, D., Graesel, C., Whitehouse, S., 2007. Is the public willing to pay for hydrogen buses? A comparative study of preferences in four cities. Energy Policy 35, 3630–3642. https://doi.org/10.1016/j.enpol.2006.12.031

O'Garra, T., Mourato, S., Pearson, P., 2005. Analysing awareness and acceptability of hydrogen vehicles: A London case study. International Journal of Hydrogen Energy 30, 649–659. https://doi.org/10.1016/j.ijhydene.2004.10.008

Ogden, J.M., Yang, C.A., Nicholas, M., Lewis, F., 2014. NextSTEPS white paper: the hydrogen transition (No. UCD-ITS-RR-14-11). Institute of Transportation Studies, University of California, Davis, California, USA.

O'Hayre, R., Cha, S.-W., Colella, W., Prinz, F.B., 2016. Fuel Cell Fundamentals. John Wiley & Sons.

Ohi, J., Vandeborgh, N., Voecks, G., 2016. Hydrogen Fuel Quality Specifications for Polymer Electrolyte Fuel Cells in Road Vehicles. U.S. Department of Energy.

Ono, K., Kato, E., Tsunemi, K., 2019. Does risk information change the acceptance of hydrogen refueling stations in the general Japanese population? International Journal of Hydrogen Energy 44, 16038–16047. https://doi.org/10.1016/j.ijhydene.2019.04.257

Onwuegbuzie, A.J., 2016. Seven steps to a comprehensive literature review: a multimodal and cultural approach, 1st edition. ed. Sage Publications, Thousand Oaks, CA.

Panik, F., 1998. Fuel cells for vehicle applications in cars - bringing the future closer. Journal of Power Sources 71, 36–38. https://doi.org/10.1016/S0378-7753(97)02805-X

Pantano, E., Di Pietro, L., 2012. Understanding Consumer's Acceptance of Technology-Based Innovations in Retailing. Journal of technology management & innovation 7, 1–19. https://doi.org/10.4067/S0718-27242012000400001

Parks, G., 2014. Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs Independent Review. https://doi.org/10.13140/RG.2.2.23768.34562

Penconi, M., Rossi, F., Ortica, F., Elisei, F., Gentili, P., 2015. Hydrogen Production from Water by Photolysis, Sonolysis and Sonophotolysis with Solid Solutions of Rare Earth, Gallium and Indium Oxides as Heterogeneous Catalysts. Sustainability 7, 9310–9325. https://doi.org/10.3390/su7079310

Penev, M., Zuboy, J., Hunter, C., 2019. Economic analysis of a high-pressure urban pipeline concept (HyLine) for delivering hydrogen to retail fueling stations. Transportation Research Part D: Transport and Environment 77, 92–105. https://doi.org/10.1016/j.trd.2019.10.005

Perez, J.M., Casero, P., 2019. eLY4OFF PEM electrolysers for operation with offgrid renewable installations. Analysis of demonstration phase results (Deliverable D5.2). Huesca, Spain.

Pino, Fco.J., Valverde, L., Rosa, F., 2011. Influence of wind turbine power curve and electrolyzer operating temperature on hydrogen production in wind–hydrogen systems. Journal of Power Sources, CONAPPICE 2010 196, 4418–4426. https://doi.org/10.1016/j.jpowsour.2010.10.060

Popa, V., Ion, I., Popa, C.L., 2016. Thermo-Economic Analysis of an Air-to-Water Heat Pump. Energy Procedia, EENVIRO-YRC 2015 - Bucharest 85, 408–415. https://doi.org/10.1016/j.egypro.2015.12.221

Pragma Industries, 2017. Technical characteristics of $H_2$ Alpha bike.

Pratt, J., Terlip, D., Ainscough, C., Kurtz, J., Elgowainy, A., 2015. H2FIRST Reference Station Design Task: Project Deliverable 2-2. National Renewable Energy Laboratory (NREL), USA.

Priessner, A., Sposato, R., Hampl, N., 2018. Predictors of electric vehicle adoption: An analysis of potential electric vehicle drivers in Austria. Energy Policy 122, 701–714. https://doi.org/10.1016/j.enpol.2018.07.058

Qadrdan, M., Shayegan, J., 2008. Economic assessment of hydrogen fueling station, a case study for Iran. Renewable Energy 33, 2525–2531. https://doi.org/10.1016/j.renene.2008.02.014

Qin, N., Brooker, P., 2014. Hydrogen Fueling Stations Infrastructure (Semi-annual project report). University of Central Florida, Cocoa, FL, USA.

Qin, N., Brooker, P., Raissi, A., 2017. Fuel Cell Vehicle Technologies, Infrastructure and Requirements. Cocoa, FL, USA.

Rasmussen, M.G., Andresen, G.B., Greiner, M., 2012. Storage and balancing synergies in a fully or highly renewable pan-European power system. Energy Policy, Renewable Energy in China 51, 642–651. https://doi.org/10.1016/j.enpol.2012.09.009

Reddi, K., Elgowainy, A., Rustagi, N., Gupta, E., 2017. Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen. International Journal of Hydrogen Energy 42, 21855–21865. https://doi.org/10.1016/j.ijhydene.2017.05.122

Reichmuth, D.S., Lutz, A.E., Manley, D.K., Keller, J.O., 2013. Comparison of the technical potential for hydrogen, battery electric, and conventional light-duty vehicles to reduce greenhouse gas emissions and petroleum consumption in the United States. International Journal of Hydrogen Energy 38, 1200–1208. https://doi.org/10.1016/j.ijhydene.2012.10.047

RIX Industries, 2019. 2TX and 3TX series [WWW Document]. URL https://www.rixindustries.com/industrial-compressors/2tx-and-3tx

Robinius, M., Linβen, J., Grube, T., Reuβ, M., Stenzel, P., Syranidis, K., Kuckertz, P., Stolten, D., 2018. Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles. Julich Forschungzentrum.

Robledo, C.B., van Leeuwen, L.B., van Wijk, A.J.M., 2019. Hydrogen fuel cell scooter with plug-out features for combined transport and residential power generation. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.04.103

Rodríguez, R.A., Becker, S., Andresen, G.B., Heide, D., Greiner, M., 2014. Transmission needs across a fully renewable European power system. Renewable Energy 63, 467–476. https://doi.org/10.1016/j.renene.2013.10.005

Rosengren, J., 2018. SE LISTEN: Disse (familie)biler kører længst på literen. Newsbreak.dk. URL https://newsbreak.dk/hvor-langt-paa-literen/ (accessed 12.5.19).

SAE, 2016. Hydrogen Fuel Cell Vehicle Technology Roadmap. Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles, China.

Salgi, G., Donslund, B., Alberg Østergaard, P., 2008. Energy system analysis of utilizing hydrogen as an energy carrier for wind power in the transportation sector in Western Denmark. Utilities

Policy, Sustainable Energy and Transportation Systems 16, 99–106. https://doi.org/10.1016/j.jup.2007.11.004

Salmeron-Manzano, E., Manzano-Agugliaro, F., 2018. The Electric Bicycle: Worldwide Research Trends. Energies 11, 1894. https://doi.org/10.3390/en11071894

Samaniego, J., Alija, F., Sanz, S., Valmaseda, C., Frechoso, F., 2008. Economic and technical analysis of a hybrid wind fuel cell energy system. Renewable Energy 33, 839–845. https://doi.org/10.1016/j.renene.2007.09.023

San Martin, I., Ursúa, A., Sanchis, P., 2014. Modelling of PEM Fuel Cell Performance: Steady-State and Dynamic Experimental Validation. Energies 7, 670–700. https://doi.org/10.3390/en7020670

Schenk, N.J., Moll, H.C., Potting, J., Benders, R.M.J., 2007. Wind energy, electricity, and hydrogen in the Netherlands. Energy 32, 1960–1971. https://doi.org/10.1016/j.energy.2007.02.002

Schepers, J., Wetzels, M., 2007. A meta-analysis of the technology acceptance model: Investigating subjective norm and moderation effects. Information & Management 44, 90–103. https://doi.org/10.1016/j.im.2006.10.007

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., Few, S., 2017. Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy 42, 30470–30492. https://doi.org/10.1016/j.ijhydene.2017.10.045

Schmoyer, R.L., Truett, T., Cooper, C., 2006. Results of the 2004 knowledge and opinions surveys for the baseline knowkedge assessment of the U.S. department of energy hydrogen program. Washington D.C., USA.

Schroeder, A., 2011. Modeling storage and demand management in power distribution grids. Applied Energy 88, 4700–4712. https://doi.org/10.1016/j.apenergy.2011.06.008

Serrao, L., Onori, S., Rizzoni, G., Guezennec, Y., 2009. A Novel Model-Based Algorithm for Battery Prognosis. IFAC Proceedings Volumes 42, 923–928. https://doi.org/10.3182/20090630-4-ES-2003.00152

Shabani, M.J., Moghaddas-Tafreshi, S.M., 2020. Fully-decentralized coordination for simultaneous hydrogen, power, and heat interaction in a multi-carrier-energy system considering private ownership. Electric Power Systems Research 180, 106099. https://doi.org/10.1016/j.epsr.2019.106099

Shafiei, E., Davidsdottir, B., Leaver, J., Stefansson, H., Asgeirsson, E.I., 2017. Energy, economic, and mitigation cost implications of transition toward a carbon-neutral transport sector: A simulation-based comparison between hydrogen and electricity. Journal of Cleaner Production 141, 237–247. https://doi.org/10.1016/j.jclepro.2016.09.064

Shang, J.L., Pollet, B.G., 2010. Hydrogen fuel cell hybrid scooter (HFCHS) with plug-in features on Birmingham campus. International Journal of Hydrogen Energy, Asian Hydrogen Energy Conference 2009 35, 12709–12715. https://doi.org/10.1016/j.ijhydene.2010.08.075

Shayegan, S., Hart, D., Pearson, P., Joffe, D., 2006. Analysis of the cost of hydrogen infrastructure for buses in London. Journal of Power Sources, Selected papers presented at the Ninth Grove Fuel Cell Symposium 157, 862–874. https://doi.org/10.1016/j.jpowsour.2005.12.065

Shayegan, S., Pearson, P.J.G., Hart, D., 2009. Hydrogen for buses in London: A scenario analysis of changes over time in refuelling infrastructure costs. International Journal of Hydrogen Energy 34, 8415–8427. https://doi.org/10.1016/j.ijhydene.2009.06.084

Shin, J., Hwang, W.-S., Choi, H., 2019. Can hydrogen fuel vehicles be a sustainable alternative on vehicle market?: Comparison of electric and hydrogen fuel cell vehicles. Technological Forecasting and Social Change 143, 239–248. https://doi.org/10.1016/j.techfore.2019.02.001

Siskova, M., van den Bergh, J., 2019. Optimal urban form for global and local emissions under electric vehicle and renewable energy scenarios. Urban Climate 29, 100472. https://doi.org/10.1016/j.uclim.2019.100472

Smit, R., Weeda, M., de Groot, A., 2007. Hydrogen infrastructure development in The Netherlands. International Journal of Hydrogen Energy, EHEC2005 32, 1387–1395. https://doi.org/10.1016/j.ijhydene.2006.10.044

Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., Wilhelmsson, F., 2011. Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. Futures, Special Issue: Energy Futures 43, 1105–1116. https://doi.org/10.1016/j.futures.2011.07.009

Solomin, E., Kirpichnikova, I., Amerkhanov, R., Korobatov, D., Lutovats, M., Martyanov, A., 2019. Wind-hydrogen standalone uninterrupted power supply plant for all-climate application. International Journal of Hydrogen Energy 44, 3433–3449. https://doi.org/10.1016/j.ijhydene.2018.12.001

Sovacool, B.K., Hirsh, R.F., 2008. Island wind-hydrogen energy: A significant potential US resource. Renewable Energy 33, 1928–1935. https://doi.org/10.1016/j.renene.2007.12.006

Spath, P.L., Mann, M.K., 2004. Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis (Milestone Completion Report). National Renewable Energy Laboratory (NREL), Golden CO, USA.

Stanton, N.A., 2017. Advances in Human Aspects of Transportation: Proceedings of the AHFE 2017 International Conference on Human Factors in Transportation, July 17−21, 2017, The Westin Bonaventure Hotel, Los Angeles, California, USA. Springer.

Statista, 2017. Denmark: driving license status 2017, by age group [WWW Document]. Statista. URL https://www.statista.com/statistics/754592/driving-license-status-in-denmark-in-by-age-group/ (accessed 11.8.20).

Statistics Denmark, 2019a. Population at the first day of the quarter by region, sex, age and marital status [WWW Document]. URL https://www.statbank.dk/statbank5a/selectvarval/define.asp?MainTable=FOLK1A&PLanguage=1&Tabstrip=&PXSId=0&SessID=303233273&FF=20&tfrequency=4 (accessed 11.8.20).

Statistics Denmark, 2019b. Use of internet for private purposes - per cent of the population(16-74 years) by type and internet activity [WWW Document]. URL https://www.statbank.dk/BEBRIT09 (accessed 11.8.20).

Statistics Denmark, 2018a. Population by Urban Areas [WWW Document]. Statbank Denmark. URL http://www.statbank.dk/10021 (accessed 2.10.18).

Statistics Denmark, 2018b. Annual employees income [WWW Document]. URL https://www.dst.dk/en/Statistik/emner/arbejde-indkomst-og-formue/indkomster (accessed 10.17.20).

Statistics Denmark, 2013. Earnings by occupation, sector [WWW Document]. URL https://www.statistikbanken.dk/statbank5a/SelectVarVal/Define.asp?Maintable=SLON21&PLanguage=1 (accessed 5.8.20).

Staubli systems GmbH, 2018. Quotation for Staubli quick connector RBL03.1201/IC/JE.

Stauffer, N., 2020. China's transition to electric vehicles [WWW Document]. Main. URL http://energy.mit.edu/news/chinas-transition-to-electric-vehicles/ (accessed 2.23.21).

Steffen, B., 2020. Estimating the cost of capital for renewable energy projects. Energy Economics 88, 104783. https://doi.org/10.1016/j.eneco.2020.104783

Stiller, C., Bünger, U., Møller-Holst, S., Svensson, A.M., Espegren, K.A., Nowak, M., 2010. Pathways to a hydrogen fuel infrastructure in Norway. International Journal of Hydrogen Energy, 2008 International Hydrogen Forum (HyForum2008) 35, 2597–2601. https://doi.org/10.1016/j.ijhydene.2009.04.003

SÜD, 2017. 92 new hydrogen refuelling stations worldwide in 2016 [WWW Document]. URL https://www.tuv-sud.com/news-media/news-archive/92-new-hydrogen-refuelling-stations-worldwide-in-2016

Suhr, D., 2006. The Basics of Structural Equation Modeling.

Sun, S., Jin, J., Xia, M., Liu, Y., Gao, M., Zou, C., Wang, T., Lin, Y., Wu, L., Mao, H., Wang, P., 2020. Vehicle emissions in a middle-sized city of China: Current status and future trends. Environment International 137, 105514. https://doi.org/10.1016/j.envint.2020.105514

Sundararagavan, S., Baker, E., 2012. Evaluating energy storage technologies for wind power integration. Solar Energy 86, 2707–2717. https://doi.org/10.1016/j.solener.2012.06.013

Sutrisna, M., 2009. Research Methodology in Doctoral Research: Understanding the Meaning of Conducting Qualitative Research, proceedings of the Association of Researchers in Construction Management (ARCOM) Doctoral Workshop. Liverpool, UK.

Tanç, B., Arat, H.T., Baltacıoğlu, E., Aydın, K., 2019. Overview of the next quarter century vision of hydrogen fuel cell electric vehicles. International Journal of Hydrogen Energy, 9th International Conference on Hydrogen Production (ICH2P-2018) 44, 10120–10128. https://doi.org/10.1016/j.ijhydene.2018.10.112

Tang, Y., Yuan, W., Pan, M., Wan, Z., 2011. Experimental investigation on the dynamic performance of a hybrid PEM fuel cell/battery system for lightweight electric vehicle application. Applied Energy 88, 68–76. https://doi.org/10.1016/j.apenergy.2010.07.033

Tarigan, A.K.M., Bayer, S.B., Langhelle, O., Thesen, G., 2012. Estimating determinants of public acceptance of hydrogen vehicles and refuelling stations in greater Stavanger. International Journal of Hydrogen Energy, XII International Symposium on Polymer Electrolytes: New Materials for Application in Proton Exchange Membrane Fuel Cells 37, 6063–6073. https://doi.org/10.1016/j.ijhydene.2011.12.138

Tatsuno Europe, 2019. Fuel Dispensers SUNNY-XE Euro [WWW Document]. URL https://www.tatsuno-europe.com/_en/fuel-dispensers-sunny-xe-euro.html (accessed 7.24.19).

Thesen, G., Langhelle, O., 2008. Awareness, acceptability and attitudes towards hydrogen vehicles and filling stations: A Greater Stavanger case study and comparisons with London. International Journal of Hydrogen Energy 33, 5859–5867. https://doi.org/10.1016/j.ijhydene.2008.07.006

Thomas, C.E., 2009. Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy 34, 6005–6020. https://doi.org/10.1016/j.ijhydene.2009.06.003

Toghyani, S., Afshari, E., Baniasadi, E., Atyabi, S.A., Naterer, G.F., 2018. Thermal and electrochemical performance assessment of a high temperature PEM electrolyzer. Energy 152, 237–246. https://doi.org/10.1016/j.energy.2018.03.140

Tolj, I., Lototskyy, M.V., Davids, M.W., Pasupathi, S., Swart, G., Pollet, B.G., 2013. Fuel cell-battery hybrid powered light electric vehicle (golf cart): Influence of fuel cell on the driving performance. International Journal of Hydrogen Energy 38, 10630–10639. https://doi.org/10.1016/j.ijhydene.2013.06.072

Tso, C., Chang, S.-Y., 2003. A viable niche market—fuel cell scooters in Taiwan. International Journal of Hydrogen Energy, Market Challenges of Fuel Cell Commercialization 28, 757–762. https://doi.org/10.1016/S0360-3199(02)00245-8

Tso, C., Huang, L.-H., Tseng, C.-J., 2012. Hydrogen Scooter Testing and Verification Program. Energy Procedia, WHEC 2012 Conference Proceedings – 19th World Hydrogen Energy Conference 29, 633–643. https://doi.org/10.1016/j.egypro.2012.09.073

Úbeda, D., Pinar, F.J., Orozco, D.C., Cañizares, P., Rodrigo, M.A., Lobato, J., 2012. Life study of a PBI-PEM fuel cell by current distribution measurement. J Appl Electrochem 42, 711–718. https://doi.org/10.1007/s10800-012-0448-7

UK gov, 2020. Full car driving licence holders by age and gender [WWW Document]. Driving licence holding and vehicle availability. URL https://www.gov.uk/government/statistical-data-sets/nts02-driving-licence-holders (accessed 11.10.20).

Ulleberg, Ø., 2003. Modeling of advanced alkaline electrolyzers: a system simulation approach. International Journal of Hydrogen Energy 28, 21–33. https://doi.org/10.1016/S0360-3199(02)00033-2

Ulleberg, Ø., Hancke, R., 2020. Techno-economic calculations of small-scale hydrogen supply systems for zero emission transport in Norway. International Journal of Hydrogen Energy, International Hydrogen and Fuel Cell Conference 2018, Trondheim, Norway 45, 1201–1211. https://doi.org/10.1016/j.ijhydene.2019.05.170

Ulleberg, Ø., Nakken, T., Eté, A., 2010. The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools. International Journal of Hydrogen Energy 35, 1841–1852. https://doi.org/10.1016/j.ijhydene.2009.10.077

Unger, E.A., Ulfarsson, G.F., Gardarsson, S.M., Matthiasson, T., 2018. The effect of wind energy production on cross-border electricity pricing: The case of western Denmark in the Nord Pool market. Economic Analysis and Policy 58, 121–130. https://doi.org/10.1016/j.eap.2018.01.006

United Nations, 2020. What is the Kyoto Protocol? [WWW Document]. URL https://unfccc.int/kyoto_protocol (accessed 12.5.19).

United Nations, 2019a. Action on Climate and Sustainable Development Goals [WWW Document]. URL https://unfccc.int/topics/action-on-climate-and-sdgs/action-on-climate-and-sdgs (accessed 12.5.19).

United Nations, 2019b. Kyoto Protocol - Targets for the first commitment period [WWW Document]. Climate Change. URL https://unfccc.int/process-and-meetings/the-kyoto-protocol/what-is-the-kyoto-protocol/kyoto-protocol-targets-for-the-first-commitment-period (accessed 6.24.19).

US Department of Energy, 2018d. Hydrogen Pipelines [WWW Document]. URL https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

US Department of Energy, 2018e. Hydrogen Production: Natural Gas Reforming [WWW Document]. URL https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

US Department of Energy, 2018f. Alternative Fuels Data Center: Hydrogen Fueling Station Locations [WWW Document]. URL https://www.afdc.energy.gov/fuels/hydrogen_locations.html#/analyze?fuel=HY&show_private=true&hy_nonretail=true

Usta, I., 2016. An innovative estimation method regarding Weibull parameters for wind energy applications. Energy 106, 301–314. https://doi.org/10.1016/j.energy.2016.03.068

Uyar, T.S., Beşikci, D., Sulukan, E., 2019. An urban techno-economic hydrogen penetration scenario analysis for Burdur, Turkey. International Journal of Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.05.144

Valverde-Isorna, L., Ali, D., Hogg, D., Abdel-Wahab, M., 2016. Modelling the performance of wind–hydrogen energy systems: Case study the Hydrogen Office in Scotland/UK. Renewable and Sustainable Energy Reviews 53, 1313–1332. https://doi.org/10.1016/j.rser.2015.08.044

van Leeuwen, C., Mulder, M., 2018. Power-to-gas in electricity markets dominated by renewables. Applied Energy 232, 258–272. https://doi.org/10.1016/j.apenergy.2018.09.217

Varkaraki, E., Lymberopoulos, N., Zoulias, E., Kalyvas, E., Christodoulou, C., Karagiorgis, G., Stolzenburg, K., 2006. Experiences from the operation of a wind-hydrogen pilot unit. World Hydrogen Energy Conference (WHEC-2006), Lyon, France.

Velazquez Abad, A., 2017. Techno-economic and environmental comparison between battery and fuel cell electric vehicles (MBA Dissertation). Southampton University, Southampton.

Venkatesh, V., Bala, H., 2008. Technology Acceptance Model 3 and a Research Agenda on Interventions. Decision Sciences 39, 273–315. https://doi.org/10.1111/j.1540-5915.2008.00192.x

Viesi, D., Crema, L., Testi, M., 2017. The Italian hydrogen mobility scenario implementing the European directive on alternative fuels infrastructure (DAFI 2014/94/EU). International Journal of Hydrogen Energy 42, 27354–27373. https://doi.org/10.1016/j.ijhydene.2017.08.203

von Helmolt, R., Eberle, U., 2007. Fuel cell vehicles: Status 2007. Journal of Power Sources 165, 833–843. https://doi.org/10.1016/j.jpowsour.2006.12.073

Wang, N., Tang, L., Pan, H., 2018. Analysis of public acceptance of electric vehicles: An empirical study in Shanghai. Technological Forecasting and Social Change 126, 284–291. https://doi.org/10.1016/j.techfore.2017.09.011

Wang, Y., Kowal, J., Leuthold, M., Sauer, D.U., 2012. Storage System of Renewable Energy Generated Hydrogen for Chemical Industry. Energy Procedia, WHEC 2012 Conference Proceedings – 19th World Hydrogen Energy Conference 29, 657–667. https://doi.org/10.1016/j.egypro.2012.09.076

Wang, Y., Moura, S.J., Advani, S.G., Prasad, A.K., 2019. Power management system for a fuel cell/battery hybrid vehicle incorporating fuel cell and battery degradation. International Journal of Hydrogen Energy 44, 8479–8492. https://doi.org/10.1016/j.ijhydene.2019.02.003

Wasserstoff-Tankstellen weltweit, 2019. Hydrogen Refuelling Stations Denmark [WWW Document]. URL https://www.netinform.de/h2/h2stations/default.aspx (accessed 12.5.19).

Wasserstoff-Tankstellen weltweit, 2017. Hydrogen Refuelling Stations Worldwide [WWW Document]. H2-Stations. URL https://www.netinform.de/H2/H2Stations/Default.aspx (accessed 1.29.18).

Webster, C., 1963. Richard Towneley and Boyle's Law. Nature 197, 226–228. https://doi.org/10.1038/197226a0

Weeda, M., Elgowainy, A., 2015. Large-Scale Hydrogen Delivery Infrastructure. IEA, Netherlands.

Weidner, S., Faltenbacher, M., François, I., Thomas, D., Skùlason, J.B., Maggi, C., 2018. Feasibility study of large scale hydrogen power-to-gas applications and cost of the systems evolving with scaling up in Germany, Belgium and Iceland. International Journal of Hydrogen Energy 43, 15625–15638. https://doi.org/10.1016/j.ijhydene.2018.06.167

Weinert, J.X., 2005. A Near-Term Economic Analysis of Hydrogen Fueling Stations.

Widera, B., 2020. Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. Thermal Science and Engineering Progress 16, 100460. https://doi.org/10.1016/j.tsep.2019.100460

Wietschel, M., Hasenauer, U., de Groot, A., 2006. Development of European hydrogen infrastructure scenarios—CO2 reduction potential and infrastructure investment. Energy Policy, Hydrogen 34, 1284–1298. https://doi.org/10.1016/j.enpol.2005.12.019

World Bank, 2019. Commodity Markets - price forecasts [WWW Document]. The World Bank. URL https://www.worldbank.org/en/research/commodity-markets (accessed 12.12.19).

Wu, X., Hu, X., Yin, X., Li, L., Zeng, Z., Pickert, V., 2019. Convex programming energy management and components sizing of a plug-in fuel cell urban logistics vehicle. Journal of Power Sources 423, 358–366. https://doi.org/10.1016/j.jpowsour.2019.03.044

Wulf, C., Kaltschmitt, M., 2018. Hydrogen Supply Chains for Mobility-Environmental and Economic Assessment. Sustainability 10. https://doi.org/10.3390/su10061699

Xu, X., Xu, B., Dong, J., Liu, X., 2017. Near-term analysis of a roll-out strategy to introduce fuel cell vehicles and hydrogen stations in Shenzhen China. Applied Energy 196, 229–237. https://doi.org/10.1016/j.apenergy.2016.11.048

Xydis, G., 2013a. Comparison study between a Renewable Energy Supply System and a supergrid for achieving 100% from renewable energy sources in Islands. International Journal of Electrical Power & Energy Systems 46, 198–210. https://doi.org/10.1016/j.ijepes.2012.10.046

Xydis, G., 2013b. A techno-economic and spatial analysis for the optimal planning of wind energy in Kythira island, Greece. International Journal of Production Economics 146, 440–452. https://doi.org/10.1016/j.ijpe.2013.02.013

Yamada, H., Inomata, S., Tanimoto, H., Hata, H., Tonokura, K., 2018. Estimation of refueling emissions based on theoretical model and effects of E10 fuel on refueling and evaporative emissions from gasoline cars. Science of The Total Environment 622–623, 467–473. https://doi.org/10.1016/j.scitotenv.2017.11.339

Yang, Y., 2017. Beyond the conventional "life cycle" assessment. Biofuel Research Journal 4, 637–637. https://doi.org/10.18331/BRJ2017.4.3.2

Yetano Roche, M., Mourato, S., Fischedick, M., Pietzner, K., Viebahn, P., 2010. Public attitudes towards and demand for hydrogen and fuel cell vehicles: A review of the evidence and methodological implications. Energy Policy, The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers 38, 5301–5310. https://doi.org/10.1016/j.enpol.2009.03.029

Yuan, R.-Q., Tao, X., Yang, X.-L., 2019. CO2 emission of urban passenger transportation in China from 2000 to 2014. Advances in Climate Change Research 10, 59–67. https://doi.org/10.1016/j.accre.2019.03.005

Zachariah-Wolff, J.L., Hemmes, K., 2006. Public Acceptance of Hydrogen in the Netherlands: Two Surveys That Demystify Public Views on a Hydrogen Economy. Bulletin of Science, Technology & Society 26, 339–345. https://doi.org/10.1177/0270467606290308

Zhang, G., Wan, X., 2014. A wind-hydrogen energy storage system model for massive wind energy curtailment. International Journal of Hydrogen Energy 39, 1243–1252. https://doi.org/10.1016/j.ijhydene.2013.11.003

Zhao, G., Pedersen, A.S., 2018. Life Cycle Assessment of Hydrogen Production and Consumption in an Isolated Territory. Procedia CIRP, 25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark 69, 529–533. https://doi.org/10.1016/j.procir.2017.11.100

Ziegler, A., 2012. Individual characteristics and stated preferences for alternative energy sources and propulsion technologies in vehicles: A discrete choice analysis for Germany. Transportation Research Part A: Policy and Practice 46, 1372–1385. https://doi.org/10.1016/j.tra.2012.05.016

Zimmer, R., Welke, J., 2012. Let's go green with hydrogen! The general public's perspective. International Journal of Hydrogen Energy, HySafe 1 37, 17502–17508. https://doi.org/10.1016/j.ijhydene.2012.02.126

Zini, G., Tartarini, P., 2010. Wind-hydrogen energy stand-alone system with carbon storage: Modeling and simulation. Renewable Energy 35, 2461–2467. https://doi.org/10.1016/j.renene.2010.03.001

# APPENDICES

## Appendix A

### A1 Survey's questionnaire

1. Gender
   - Male
   - Female
2. Age group
   - Under 18
   - 18 - 24
   - 25 - 34
   - 35 - 44
   - 45 - 54
   - 55 - 64
   - 65 - 74
   - 75 or older
3. Education
   - Primary education
   - Secondary education
   - University BSc level
   - MSc or PhD level
4. Net annual income in DKK (comma separator depicts thousands)
   - 0 - 200,000
   - 200,001 - 300,000
   - 300,001 - 400,000
   - 400,001 - 500,000
   - 500,001 - 600,000
   - 600,001 or more
5. Which of the following describes you better in terms of being environmental friendly?
   - It's part of my everyday life
   - I act as far as possible I can
   - I think about it, but don't act on it
   - I'm not thinking about that

6. Did you ever have an AFV or know someone in your innermost circle owing an AFV? (AFV corresponds to "Alternative Fuel Vehicle" including battery electric, plug-in hybrid electric, and fuel cell electric vehicles)
   - Yes
   - No
   - Maybe
7. Do you have any previous experience with hydrogen cars (fuel cell vehicles)?
   - I own/lease a hydrogen car
   - I have used a hydrogen car in the past
   - I know someone who has used a hydrogen car or know someone who has a hydrogen car
   - I have not used a hydrogen car and know no one who has
8. How many times in the last year have you noticed a newspaper/online article or other media support concerning hydrogen vehicles?
   - None
   - 1 - 2
   - 2 - 5
   - More than 5
9. How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)?

   (I know nothing) 1 2 3 4 5 (I know a lot)
10. Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is?
    - Not safe
    - Less safe
    - The same
    - Safer
11. Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car?
    - Yes
    - No
    - Maybe

12. Please choose how much you agree or disagree with the following statements if you were to buy a hydrogen car:

| | Disagree | Mostly disagree | Neutral | Mostly agree | Agree |
|---|---|---|---|---|---|
| The price of a hydrogen car is currently 515,000-583,000 DKK. I think that it is too expensive. | | | | | |
| I believe that the fuel cost of hydrogen cars needs to be reduced more. | | | | | |
| There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. | | | | | |
| The public media must focus more on hydrogen cars. | | | | | |
| If the hydrogen fuel price would decrease by 30% in the future (without a decrease of the vehicle's price), hydrogen cars would be more competitive. | | | | | |
| If the price of a hydrogen car would drop by 50% in the future, the hydrogen car market would be highly competitive. | | | | | |

13. By taking into account all the above, I would...

- Consider a fuel cell car as my next vehicle
- Consider buying a fuel cell car in the near future (5 years from now)
- Probably not consider buying a fuel cell vehicle in the near future
- Never purchase a fuel cell vehicle

### A2 Danish population census data

Table A2. Post-stratification weighting method input data and weight correction factors results.

| Parameter | 18-24 years old | 25-34 years old | 35-44 years old | 45-54 years old | 55-64 years old | 65-74 years old |
|---|---|---|---|---|---|---|
| Population having driving licence (males) | 171,089 | 323,354 | 307,023 | 357,452 | 331,919 | 248,542 |
| Population having driving licence (females) | 151,036 | 277,222 | 282,754 | 331,060 | 296,658 | 181,563 |

| Parameter | 18-24 years old | 25-34 years old | 35-44 years old | 45-54 years old | 55-64 years old | 65-74 years old |
|---|---|---|---|---|---|---|
| Survey population (males) | 7 | 26 | 17 | 21 | 18 | 8 |
| Survey population (females) | 10 | 20 | 13 | 14 | 4 | - |
| Weights (males) | 1.36 | 0.69 | 1.01 | 0.95 | 1.03 | 1.73 |
| Weights (females) | 0.61 | 0.56 | 0.87 | 0.95 | 2.97 | - |

# Appendix B

## B1 Knowledge of hydrogen vehicles technology

### *B1.1 Gender*

Table B1.1.1. Crosstab statistic test between participants' gender and knowledge of the technology.

| | | | Gender | | |
|---|---|---|---|---|---|
| | | | Male | Female | Total |
| How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | I know nothing | Count | $18_a$ | $22_b$ | 40 |
| | | Expected Count | 25.6 | 14.4 | 40.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 45.0% | 55.0% | 100.0% |
| | I know few | Count | $33_a$ | $17_a$ | 50 |
| | | Expected Count | 32.0 | 18.0 | 50.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 66.0% | 34.0% | 100.0% |
| | Intermediate level of knowledge | Count | $27_a$ | $8_a$ | 35 |
| | | Expected Count | 22.4 | 12.6 | 35.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 77.1% | 22.9% | 100.0% |
| | I know enough things | Count | $13_a$ | $3_a$ | 16 |
| | | Expected Count | 10.2 | 5.8 | 16.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 81.3% | 18.8% | 100.0% |
| | I know a lot | Count | $5_a$ | $4_a$ | 9 |
| | | Expected Count | 5.8 | 3.2 | 9.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 55.6% | 44.4% | 100.0% |
| Total | | Count | 96 | 54 | 150 |
| | | Expected Count | 96.0 | 54.0 | 150.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 64.0% | 36.0% | 100.0% |

Each subscript letter denotes a subset of Gender categories whose column proportions do not differ significantly from each other at the .05 level.

Table B1.1.2. Chi-square results between participants' gender and knowledge of the technology.

| | Value | df | Asymptotic Significance (2-sided) |
|---|---|---|---|
| Pearson Chi-Square | 11.323[a] | 4 | .023 |
| Likelihood Ratio | 11.435 | 4 | .022 |
| Linear-by-Linear Association | 5.125 | 1 | .024 |
| N of Valid Cases | 150 | | |

a. 1 cells (10.0%) have expected count less than 5. The minimum expected count is 3.24.

Table B1.1.3. Measure of association between participants' gender and knowledge of the technology.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance |
|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .275 | | | .023 |
| | Cramer's V | .275 | | | .023 |
| Interval by Interval | Pearson's R | -.185 | .083 | -2.296 | .023[c] |
| Ordinal by Ordinal | Spearman Correlation | -.221 | .081 | -2.755 | .007[c] |
| N of Valid Cases | | 150 | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

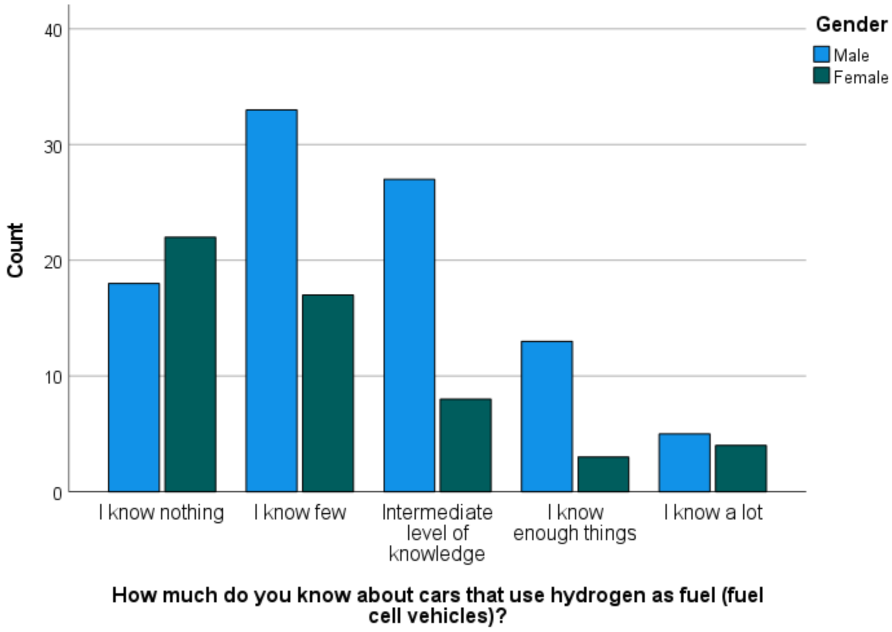



Fig. B1.1. Interaction between participants' gender and knowledge of FCEVs technology.

## *B1.2 Age*

Table B1.2.1. Crosstab statistic test between participants' age and knowledge of the technology.

| | | | Age | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 18 - 24 | 25 - 34 | 35 - 44 | 45 - 54 | 55 - 64 | 65 - 74 | Total |
| How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | I know nothing | Count | $5_{a}$ | $7_{a}$ | $8_{a}$ | $7_{a}$ | $10_{a}$ | $3_{a}$ | 40 |
| | | Expected Count | 4.2 | 7.8 | 7.6 | 8.9 | 7.8 | 3.7 | 40.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 12.5% | 17.5% | 20.0% | 17.5% | 25.0% | 7.5% | 100.0% |
| | I know few | Count | $4_{a, b}$ | $11_{a, b}$ | $7_{b}$ | $9_{a, b}$ | $15_{a}$ | $5_{a, b}$ | 51 |
| | | Expected Count | 5.3 | 10.0 | 9.7 | 11.3 | 10.0 | 4.7 | 51.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 7.8% | 21.6% | 13.7% | 17.6% | 29.4% | 9.8% | 100.0% |
| | | Count | $5_{a, b}$ | $5_{a, b}$ | $7_{a, b}$ | $12_{b}$ | $4_{a}$ | $2_{a, b}$ | 35 |
| | | Expected Count | 3.7 | 6.9 | 6.6 | 7.8 | 6.9 | 3.2 | 35.0 |

| | | | Age | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 18 - 24 | 25 - 34 | 35 - 44 | 45 - 54 | 55 - 64 | 65 - 74 | Total |
| | Intermediate level of knowledge | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 14.3% | 14.3% | 20.0% | 34.3% | 11.4% | 5.7% | 100.0% |
| | I know enough things | Count | $1_a$ | $5_a$ | $5_a$ | $4_a$ | $1_a$ | $2_a$ | 18 |
| | | Expected Count | 1.9 | 3.5 | 3.4 | 4.0 | 3.5 | 1.6 | 18.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 5.6% | 27.8% | 27.8% | 22.2% | 5.6% | 11.1% | 100.0% |
| | I know a lot | Count | $1_{a, b}$ | $2_{a, b}$ | $2_{a, b}$ | $2_{a, b}$ | $0_b$ | $2_a$ | 9 |
| | | Expected Count | .9 | 1.8 | 1.7 | 2.0 | 1.8 | .8 | 9.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 11.1% | 22.2% | 22.2% | 22.2% | 0.0% | 22.2% | 100.0% |
| Total | | Count | 16 | 30 | 29 | 34 | 30 | 14 | 153 |
| | | Expected Count | 16.0 | 30.0 | 29.0 | 34.0 | 30.0 | 14.0 | 153.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 10.5% | 19.6% | 19.0% | 22.2% | 19.6% | 9.2% | 100.0% |

Each subscript letter denotes a subset of age categories whose column proportions do not differ significantly from each other at the .05 level.

Table B1.2.2. Chi-square results between participants' age and knowledge of the technology.

| | Value | df | Asymptotic Significance (2-sided) | Monte Carlo Sig. (2-sided) Significance | Monte Carlo Sig. (2-sided) 99% Confidence Interval Lower Bound | Monte Carlo Sig. (2-sided) 99% Confidence Interval Upper Bound | Monte Carlo Sig. (1-sided) Significance | Monte Carlo Sig. (1-sided) 99% Confidence Interval Lower Bound | Monte Carlo Sig. (1-sided) 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|---|
| Pearson Chi-Square | 17.699[a] | 20 | .607 | .619[b] | .606 | .631 | | | |
| Likelihood Ratio | 19.365 | 20 | .498 | .627[b] | .614 | .639 | | | |
| Fisher-Freeman-Halton Exact Test | 17.817 | | | .562[b] | .549 | .575 | | | |
| Linear-by-Linear Association | .431[c] | 1 | .512 | .519[b] | .506 | .531 | .267[b] | .255 | .278 |
| N of Valid Cases | 153 | | | | | | | | |

a. 17 cells (56.7%) have expected count less than 5. The minimum expected count is .82.

b. Based on 10000 sampled tables with starting seed 2000000.

c. The standardized statistic is -.656.

### *B1.3 Education level*

Table B1.3.1. Crosstab statistic test between participants' education level and knowledge of the technology.

| | | | Education: Primary education | Education: Secondary education | Education: University BSc level | Education: MSc or PhD level | Total |
|---|---|---|---|---|---|---|---|
| How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | I know nothing | Count | $8_a$ | $17_{a, b}$ | $12_{a, b}$ | $4_b$ | 41 |
| | | Expected Count | 5.1 | 14.2 | 14.5 | 7.2 | 41.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 19.5% | 41.5% | 29.3% | 9.8% | 100.0% |
| | I know few | Count | $4_a$ | $15_a$ | $21_a$ | $11_a$ | 51 |
| | | Expected Count | 6.3 | 17.7 | 18.0 | 9.0 | 51.0 |

| | | | Education | | | | |
|---|---|---|---|---|---|---|---|
| | | | Primary education | Secondary education | University BSc level | MSc or PhD level | Total |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 7.8% | 29.4% | 41.2% | 21.6% | 100.0% |
| | Intermediate level of knowledge | Count | $4_a$ | $12_a$ | $13_a$ | $6_a$ | 35 |
| | | Expected Count | 4.3 | 12.1 | 12.4 | 6.2 | 35.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 11.4% | 34.3% | 37.1% | 17.1% | 100.0% |
| | I know enough things | Count | $3_a$ | $6_a$ | $5_a$ | $3_a$ | 17 |
| | | Expected Count | 2.1 | 5.9 | 6.0 | 3.0 | 17.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 17.6% | 35.3% | 29.4% | 17.6% | 100.0% |
| | I know a lot | Count | $0_a$ | $3_a$ | $3_a$ | $3_a$ | 9 |
| | | Expected Count | 1.1 | 3.1 | 3.2 | 1.6 | 9.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 0.0% | 33.3% | 33.3% | 33.3% | 100.0% |
| Total | | Count | 19 | 53 | 54 | 27 | 153 |
| | | Expected Count | 19.0 | 53.0 | 54.0 | 27.0 | 153.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 12.4% | 34.6% | 35.3% | 17.6% | 100.0% |

Each subscript letter denotes a subset of Education categories whose column proportions do not differ significantly from each other at the .05 level.

Table B1.3.2. Chi-square results between participants' education level and knowledge of the technology.

| | | | | Monte Carlo Sig. (2-sided) | | | Monte Carlo Sig. (1-sided) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 99% Confidence Interval | | | 99% Confidence Interval | |
| | Value | df | Asymptotic Significance (2-sided) | Significance | Lower Bound | Upper Bound | Significance | Lower Bound | Upper Bound |
| Pearson Chi-Square | 9.285[a] | 12 | .678 | .685[b] | .673 | .697 | | | |
| Likelihood Ratio | 10.232 | 12 | .596 | .661[b] | .649 | .673 | | | |
| Fisher-Freeman-Halton Exact Test | 9.058 | | | .687[b] | .675 | .699 | | | |
| Linear-by-Linear Association | 2.294[c] | 1 | .130 | .130[b] | .121 | .139 | .068[b] | .061 | .074 |
| N of Valid Cases | 153 | | | | | | | | |

a. 7 cells (35.0%) have expected count less than 5. The minimum expected count is 1.12.

b. Based on 10000 sampled tables with starting seed 743671174.

c. The standardized statistic is 1.515.

### *B1.4 Alternative fuel vehicle experience*

Table B1.4.1. Crosstab statistic test between participants' AFV experience and knowledge of the technology.

| | | | Did you ever have an AFV or know someone in your innermost circle owing an AFV? (AFV corresponds to "Alternative Fuel Vehicle" including battery electric, plug-in hybrid electric, and fuel cell electric vehicles) | | | |
|---|---|---|---|---|---|---|
| | | | Yes | No | Maybe | Total |
| How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | I know nothing | Count | 7 | 30 | 3 | 40 |
| | | Expected Count | 10.6 | 28.3 | 1.1 | 40.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 17.5% | 75.0% | 7.5% | 100.0% |
| | I know few | Count | 9 | 41 | 0 | 50 |
| | | Expected Count | 13.2 | 35.4 | 1.3 | 50.0 |

| | | Did you ever have an AFV or know someone in your innermost circle owing an AFV? (AFV corresponds to "Alternative Fuel Vehicle" including battery electric, plug-in hybrid electric, and fuel cell electric vehicles) | | | |
|---|---|---|---|---|---|
| | | Yes | No | Maybe | Total |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 18.0% | 82.0% | 0.0% | 100.0% |
| Intermediate level of knowledge | Count | 12 | 23 | 0 | 35 |
| | Expected Count | 9.3 | 24.8 | .9 | 35.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 34.3% | 65.7% | 0.0% | 100.0% |
| I know enough things | Count | 6 | 11 | 0 | 17 |
| | Expected Count | 4.5 | 12.0 | .5 | 17.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 35.3% | 64.7% | 0.0% | 100.0% |
| I know a lot | Count | 6 | 2 | 1 | 9 |
| | Expected Count | 2.4 | 6.4 | .2 | 9.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 66.7% | 22.2% | 11.1% | 100.0% |
| Total | Count | 40 | 107 | 4 | 151 |
| | Expected Count | 40.0 | 107.0 | 4.0 | 151.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 26.5% | 70.9% | 2.6% | 100.0% |

Table B1.4.2. Chi-square results between participants' AFV experience and knowledge of the technology.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 22.252[a] | 8 | .004 | .007 | | |
| Likelihood Ratio | 22.334 | 8 | .004 | .003 | | |
| Fisher-Freeman-Halton Exact Test | 19.788 | | | .003 | | |
| Linear-by-Linear Association | 9.767[b] | 1 | .002 | .002 | .001 | .000 |
| N of Valid Cases | 151 | | | | | |

a. 7 cells (46.7%) have expected count less than 5. The minimum expected count is .24.

b. The standardized statistic is -3.125.

Table B1.4.3. Measure of association between participants' AFV experience and knowledge of the technology.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .384 | | | .004 | .007 |
| | Cramer's V | .271 | | | .004 | .007 |
| Interval by Interval | Pearson's R | -.255 | .092 | -3.221 | .002[c] | .002 |
| Ordinal by Ordinal | Spearman Correlation | -.251 | .085 | -3.162 | .002[c] | .002 |
| N of Valid Cases | | 151 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

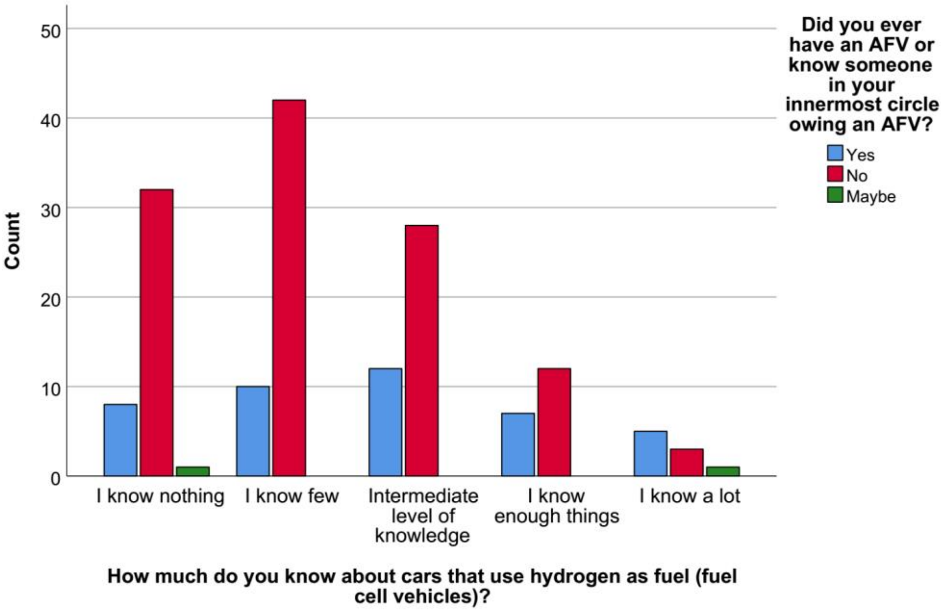



Fig. B1.4. Interaction between participants' AFV experience and knowledge of FCEVs technology.

*B1.5 Fuel cell electric vehicle experience*

Table B1.5.1. Crosstab statistic test between participants' FCEV experience and knowledge of the technology.

| | | | Do you have any previous experience with hydrogen cars (fuel cell vehicles)? | | | | |
|---|---|---|---|---|---|---|---|
| | | | I own/lease a hydrogen car | I have used a hydrogen car in the past | I know someone who has used a hydrogen car or know someone who has a hydrogen car | I have not used a hydrogen car and know no one who has | Total |
| How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | I know nothing | Count | 0 | 2 | 4 | 34 | 40 |
| | | Expected Count | .5 | 3.5 | 8.3 | 27.7 | 40.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 0.0% | 5.0% | 10.0% | 85.0% | 100.0% |
| | I know few | Count | 0 | 1 | 10 | 39 | 50 |
| | | Expected Count | .7 | 4.3 | 10.3 | 34.7 | 50.0 |

| | | Do you have any previous experience with hydrogen cars (fuel cell vehicles)? | | | | |
|---|---|---|---|---|---|---|
| | | I own/lease a hydrogen car | I have used a hydrogen car in the past | I know someone who has used a hydrogen car or know someone who has a hydrogen car | I have not used a hydrogen car and know no one who has | Total |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 0.0% | 2.0% | 20.0% | 78.0% | 100.0% |
| Intermediate level of knowledge | Count | 0 | 3 | 9 | 22 | 34 |
| | Expected Count | .5 | 2.9 | 7.0 | 23.6 | 34.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 0.0% | 8.8% | 26.5% | 64.7% | 100.0% |
| I know enough things | Count | 0 | 5 | 5 | 8 | 18 |
| | Expected Count | .2 | 1.6 | 3.7 | 12.5 | 18.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 0.0% | 27.8% | 27.8% | 44.4% | 100.0% |
| I know a lot | Count | 2 | 2 | 3 | 1 | 8 |
| | Expected Count | .1 | .7 | 1.7 | 5.5 | 8.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 25.0% | 25.0% | 37.5% | 12.5% | 100.0% |
| Total | Count | 2 | 13 | 31 | 104 | 150 |

| | | Do you have any previous experience with hydrogen cars (fuel cell vehicles)? | | | | |
|---|---|---|---|---|---|---|
| | | I own/lease a hydrogen car | I have used a hydrogen car in the past | I know someone who has used a hydrogen car or know someone who has a hydrogen car | I have not used a hydrogen car and know no one who has | Total |
| | Expected Count | 2.0 | 13.0 | 31.0 | 104.0 | 150.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 1.3% | 8.7% | 20.7% | 69.3% | 100.0% |

Table B1.5.2. Chi-square results between participants' FCEV experience and knowledge of the technology.

| | Value | df | Asymptotic Significance (2-sided) | Monte Carlo Sig. (2-sided) Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound | Monte Carlo Sig. (1-sided) Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|---|
| Pearson Chi-Square | 60.436[a] | 12 | .000 | .000[b] | .000 | .000 | | | |
| Likelihood Ratio | 36.568 | 12 | .000 | .000[b] | .000 | .000 | | | |
| Fisher-Freeman-Halton Exact Test | 34.821 | | | .000[b] | .000 | .000 | | | |
| Linear-by-Linear Association | 28.621[c] | 1 | .000 | .000[b] | .000 | .000 | .000[b] | .000 | .000 |
| N of Valid Cases | 150 | | | | | | | | |

a. 12 cells (60.0%) have expected count less than 5. The minimum expected count is .11.

b. Based on 10000 sampled tables with starting seed 743671174.

c. The standardized statistic is -5.350.

Table B1.5.3. Measure of association between participants' FCEV experience and knowledge of the technology.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Monte Carlo Significance | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound |
| Nominal by Nominal | Phi | .635 | | | .000 | .000[c] | .000 | .000 |
| | Cramer's V | .366 | | | .000 | .000[c] | .000 | .000 |
| Interval by Interval | Pearson's R | -.438 | .081 | -5.932 | .000[d] | .000[c] | .000 | .000 |
| Ordinal by Ordinal | Spearman Correlation | -.373 | .078 | -4.894 | .000[d] | .000[c] | .000 | .000 |
| N of Valid Cases | | 150 | | | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on 10000 sampled tables with starting seed 743671174.

d. Based on normal approximation.

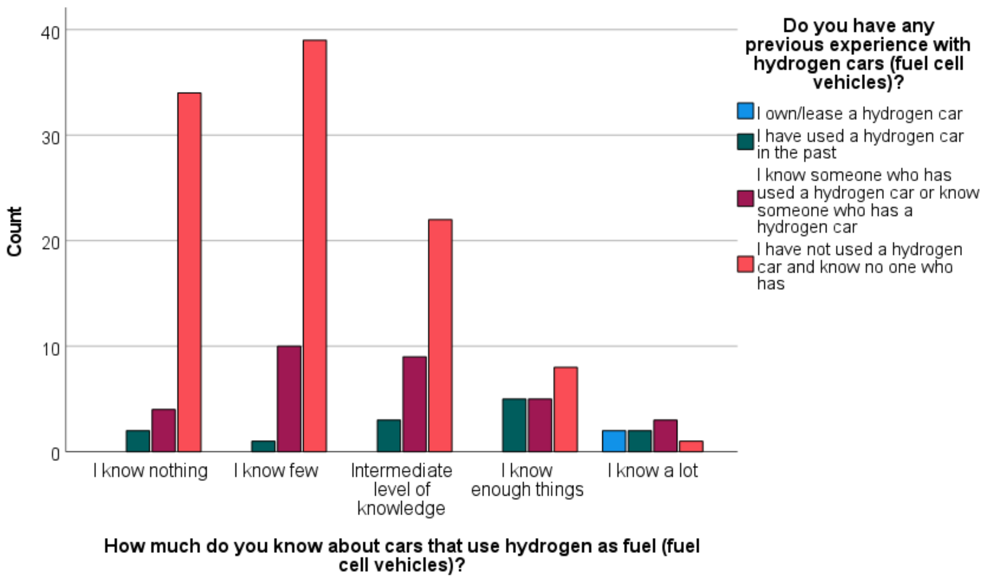



Fig. B1.5. Interaction between participants' FCEV experience and knowledge of FCEVs technology.

*B1.6 Media support*

Table B1.6.1. Crosstab statistic test between media support and knowledge of the technology by the public.

| | | | How many times in the last year have you noticed a newspaper/online article or other media support concerning hydrogen vehicles? | | | | |
|---|---|---|---|---|---|---|---|
| | | | None | 1 - 2 | 2 - 5 | More than 5 | Total |
| How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | I know nothing | Count | 22 | 12 | 2 | 4 | 40 |
| | | Expected Count | 13.2 | 14.8 | 5.1 | 7.0 | 40.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 55.0% | 30.0% | 5.0% | 10.0% | 100.0% |
| | I know few | Count | 16 | 22 | 6 | 7 | 51 |
| | | Expected Count | 16.8 | 18.8 | 6.5 | 8.9 | 51.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 31.4% | 43.1% | 11.8% | 13.7% | 100.0% |
| | Intermediate level of knowledge | Count | 6 | 13 | 8 | 7 | 34 |
| | | Expected Count | 11.2 | 12.6 | 4.3 | 5.9 | 34.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 17.6% | 38.2% | 23.5% | 20.6% | 100.0% |
| | I know enough things | Count | 2 | 7 | 3 | 4 | 16 |
| | | Expected Count | 5.3 | 5.9 | 2.0 | 2.8 | 16.0 |
| | | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 12.5% | 43.8% | 18.8% | 25.0% | 100.0% |
| | I know a lot | Count | 3 | 1 | 0 | 4 | 8 |
| | | Expected Count | 2.6 | 3.0 | 1.0 | 1.4 | 8.0 |

| | | How many times in the last year have you noticed a newspaper/online article or other media support concerning hydrogen vehicles? None | 1 - 2 | 2 - 5 | More than 5 | Total |
|---|---|---|---|---|---|---|
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 37.5% | 12.5% | 0.0% | 50.0% | 100.0% |
| Total | Count | 49 | 55 | 19 | 26 | 149 |
| | Expected Count | 49.0 | 55.0 | 19.0 | 26.0 | 149.0 |
| | % within How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | 32.9% | 36.9% | 12.8% | 17.4% | 100.0% |

Table B1.6.2. Chi-square results between media support and knowledge of the technology by the public.

| | Value | df | Asymptotic Significance (2-sided) | Monte Carlo Sig. (2-sided) Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound | Monte Carlo Sig. (1-sided) Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|---|
| Pearson Chi-Square | 26.764[a] | 12 | .008 | .007[b] | .005 | .009 | | | |
| Likelihood Ratio | 26.780 | 12 | .008 | .014[b] | .011 | .016 | | | |
| Fisher-Freeman-Halton Exact Test | 24.463 | | | .008[b] | .006 | .011 | | | |
| Linear-by-Linear Association | 13.049[c] | 1 | .000 | .000[b] | .000 | .001 | .000[b] | .000 | .001 |
| N of Valid Cases | 149 | | | | | | | | |

a. 7 cells (35.0%) have expected count less than 5. The minimum expected count is 1.02.

b. Based on 10000 sampled tables with starting seed 329836257.

c. The standardized statistic is 3.612.

Table B1.6.3. Measure of association between media support and knowledge of the technology by public.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Monte Carlo Significance: Significance | Monte Carlo Significance: 99% Confidence Interval Lower Bound | Monte Carlo Significance: 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .424 | | | .008 | .007[c] | .005 | .009 |
| | Cramer's V | .245 | | | .008 | .007[c] | .005 | .009 |
| Interval by Interval | Pearson's R | .297 | .085 | 3.770 | .000[d] | .000[c] | .000 | .001 |
| Ordinal by Ordinal | Spearman Correlation | .319 | .079 | 4.080 | .000[d] | .000[c] | .000 | .000 |
| N of Valid Cases | | 149 | | | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on 10000 sampled tables with starting seed 329836257.

d. Based on normal approximation.

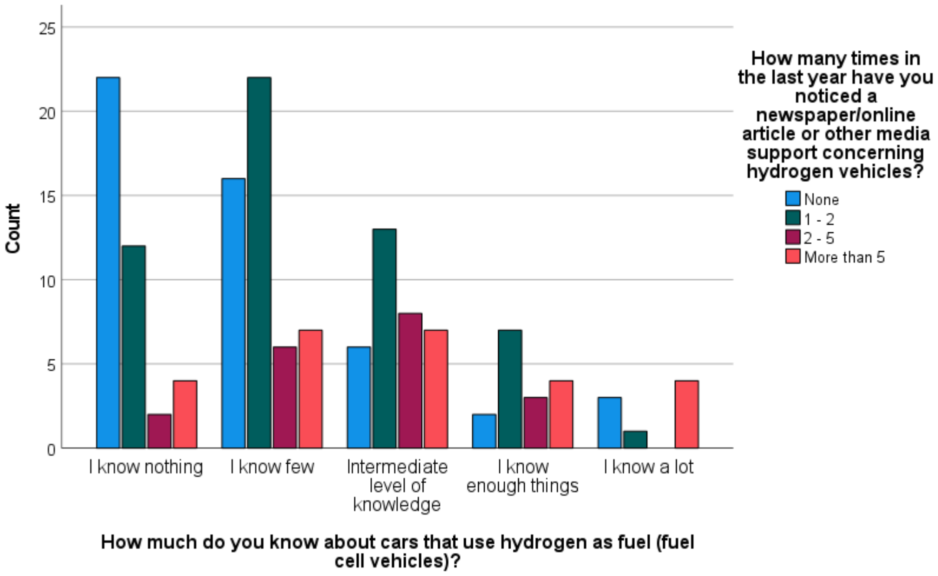



Fig. B1.6. Interaction between media support and knowledge of FCEV technology by the public.

## B2 Willingness to purchase a fuel cell electric vehicle

### *B2.1 Knowledge of hydrogen vehicle technology*

Table B2.1.1. Crosstab statistic test between participants' knowledge of the technology and willingness to purchase a FCEV.

| | | | How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | I know nothing | I know few | Intermediate level of knowledge | I know enough things | I know a lot | Total |
| Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | Yes | Count | $3_{a}$ | $11_{a, b}$ | $8_{a, b}$ | $3_{a, b}$ | $4_{b}$ | 29 |
| | | Expected Count | 7.6 | 9.7 | 6.7 | 3.2 | 1.7 | 29.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 10.3% | 37.9% | 27.6% | 10.3% | 13.8% | 100.0% |
| | No | Count | $16_{a}$ | $11_{a}$ | $10_{a}$ | $4_{a}$ | $4_{a}$ | 45 |
| | | Expected Count | 11.8 | 15.1 | 10.4 | 5.0 | 2.7 | 45.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 35.6% | 24.4% | 22.2% | 8.9% | 8.9% | 100.0% |
| | Maybe | Count | $21_{a}$ | $29_{a}$ | $17_{a}$ | $10_{a}$ | $1_{b}$ | 78 |
| | | Expected Count | 20.5 | 26.2 | 18.0 | 8.7 | 4.6 | 78.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 26.9% | 37.2% | 21.8% | 12.8% | 1.3% | 100.0% |
| Total | | Count | 40 | 51 | 35 | 17 | 9 | 152 |
| | | Expected Count | 40.0 | 51.0 | 35.0 | 17.0 | 9.0 | 152.0 |

| | How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? | | | | | |
|---|---|---|---|---|---|---|
| | I know nothing | I know few | Intermediate level of knowledge | I know enough things | I know a lot | Total |
| % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 26.3% | 33.6% | 23.0% | 11.2% | 5.9% | 100.0% |

Each subscript letter denotes a subset of How much do you know about cars that use hydrogen as fuel (fuel cell vehicles)? categories whose column proportions do not differ significantly from each other at the .05 level.

Table B2.1.2. Chi-square results between participants' knowledge of the technology and willingness to purchase a FCEV.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 17.763[a] | 8 | .023 | .022 | | |
| Likelihood Ratio | 18.336 | 8 | .019 | .026 | | |
| Fisher's Exact Test | 17.705 | | | .017 | | |
| Linear-by-Linear Association | 3.340[b] | 1 | .068 | .071 | .038 | .007 |
| N of Valid Cases | 161 | | | | | |

a. 4 cells (26.7%) have expected count less than 5. The minimum expected count is 1.57.

b. The standardized statistic is -1.827.

Table B2.1.3. Measure of association between participants' knowledge of the technology and willingness to purchase a FCEV.

| | | Value | Approximate Significance | Exact Significance |
|---|---|---|---|---|
| Nominal by Nominal | Phi | .332 | .023 | .022 |
| | Cramer's V | .235 | .023 | .022 |
| N of Valid Cases | | 161 | | |

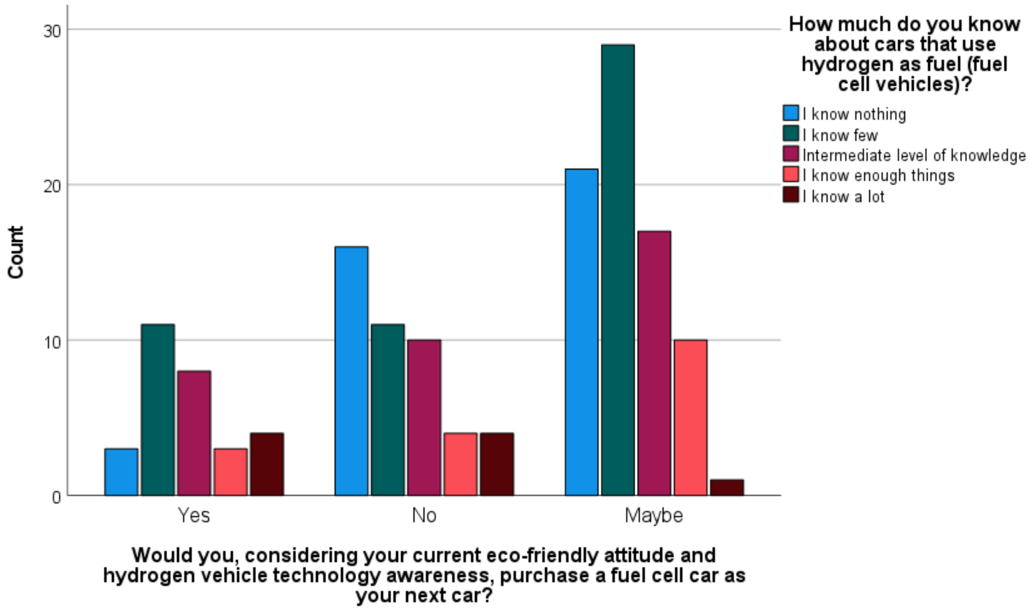



Fig. B2.1. Interaction between participants' knowledge of the technology and willingness to purchase a FCEV.

### *B2.2 Individual's environmental attitude*

Table B2.2.1. Crosstab statistic test between participants' environmental attitude and willingness to purchase a FCEV.

| | | | Which of the following describes you better in terms of being environmental friendly? | | | | |
|---|---|---|---|---|---|---|---|
| | | | It's part of my everyday life | I act as far as possible I can | I think about it, but don't act on it | I'm not thinking about that | Total |
| Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | Yes | Count | $2_{a, b}$ | $24_{b}$ | $2_{a}$ | $0_{a, b}$ | 28 |
| | | Expected Count | 4.1 | 16.9 | 6.1 | .9 | 28.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 7.1% | 85.7% | 7.1% | 0.0% | 100.0% |
| | No | Count | $8_{a, b}$ | $22_{b}$ | $11_{b}$ | $4_{a}$ | 45 |
| | | Expected Count | 6.5 | 27.2 | 9.8 | 1.5 | 45.0 |

| | | | Which of the following describes you better in terms of being environmental friendly? | | | | |
|---|---|---|---|---|---|---|---|
| | | | It's part of my everyday life | I act as far as possible I can | I think about it, but don't act on it | I'm not thinking about that | Total |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 17.8% | 48.9% | 24.4% | 8.9% | 100.0% |
| | Maybe | Count | $12_a$ | $46_a$ | $20_a$ | $1_a$ | 79 |
| | | Expected Count | 11.4 | 47.8 | 17.2 | 2.6 | 79.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 15.2% | 58.2% | 25.3% | 1.3% | 100.0% |
| Total | | Count | 22 | 92 | 33 | 5 | 152 |
| | | Expected Count | 22.0 | 92.0 | 33.0 | 5.0 | 152.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 14.5% | 60.5% | 21.7% | 3.3% | 100.0% |

Each subscript letter denotes a subset of Which of the following describes you better in terms of being environmental friendly? categories whose column proportions do not differ significantly from each other at the .05 level.

Table B2.2.2. Chi-square results between participants' environmental attitude and willingness to purchase a FCEV.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 14.977[a] | 6 | .020 | .019 | | |
| Likelihood Ratio | 15.720 | 6 | .015 | .020 | | |
| Fisher-Freeman-Halton Exact Test | 13.194 | | | .027 | | |
| Linear-by-Linear Association | .203[b] | 1 | .652 | .704 | .356 | .055 |
| N of Valid Cases | 152 | | | | | |

a. 4 cells (33.3%) have expected count less than 5. The minimum expected count is .92.

b. The standardized statistic is .451.

Table B2.2.3. Measure of association between participants' environmental attitude and willingness to purchase a FCEV.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .314 | | | .020 | .019 |
| | Cramer's V | .222 | | | .020 | .019 |
| Interval by Interval | Pearson's R | .037 | .065 | .450 | .654[c] | .704 |
| Ordinal by Ordinal | Spearman Correlation | .038 | .072 | .460 | .646[c] | .646 |
| N of Valid Cases | | 152 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

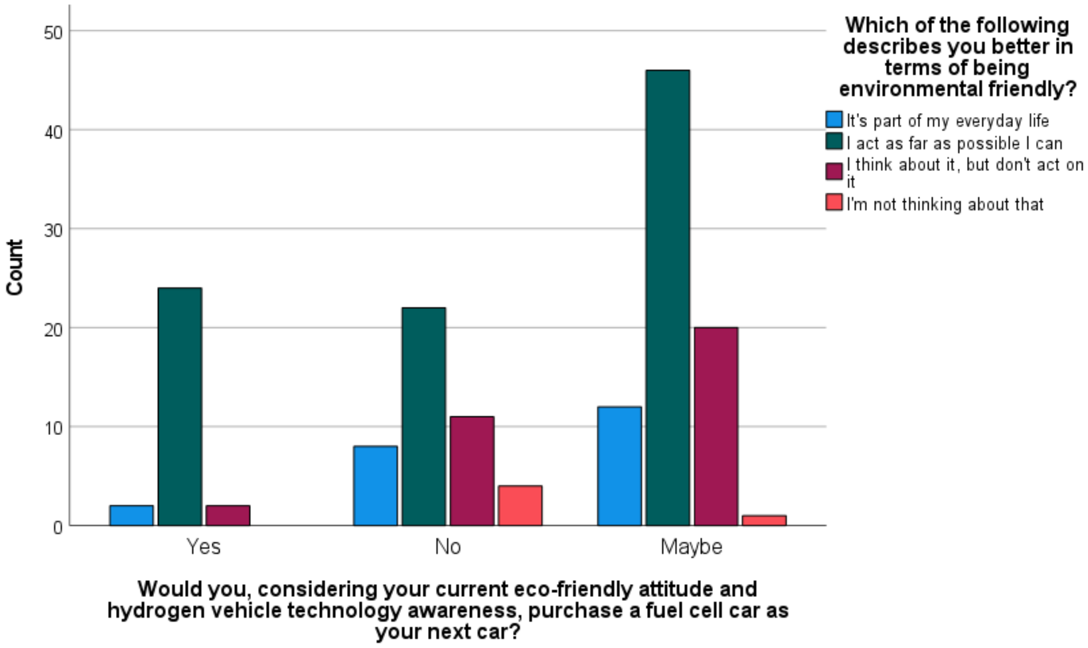



Fig. B2.2. Interaction between participants' environmental attitude and willingness to purchase a FCEV.

*B2.3 Fuel cell electric vehicle experience*

Table B2.3.1. Crosstab statistic test between participants' FCEV experience and willingness to purchase a FCEV.

| | | | Do you have any previous experience with hydrogen cars (fuel cell vehicles)? | | | | |
|---|---|---|---|---|---|---|---|
| | | | I own/lease a hydrogen car | I have used a hydrogen car in the past | I know someone who has used a hydrogen car or know someone who has a hydrogen car | I have not used a hydrogen car and know no one who has | Total |
| Would you, considering your | Yes | Count | $2_a$ | $5_{a, b}$ | $8_{b, c}$ | $13_c$ | 28 |
| | | Expected Count | .4 | 2.4 | 5.9 | 19.3 | 28.0 |

| | | | Do you have any previous experience with hydrogen cars (fuel cell vehicles)? | | | | Total |
|---|---|---|---|---|---|---|---|
| | | | I own/lease a hydrogen car | I have used a hydrogen car in the past | I know someone who has used a hydrogen car or know someone who has a hydrogen car | I have not used a hydrogen car and know no one who has | |
| current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 7.1% | 17.9% | 28.6% | 46.4% | 100.0% |
| | No | Count | $0_a$ | $5_a$ | $8_a$ | $32_a$ | 45 |
| | | Expected Count | .6 | 3.8 | 9.5 | 31.1 | 45.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 0.0% | 11.1% | 17.8% | 71.1% | 100.0% |
| | Maybe | Count | $0_{a, b}$ | $3_b$ | $16_{a, b}$ | $60_a$ | 79 |
| | | Expected Count | 1.0 | 6.8 | 16.6 | 54.6 | 79.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 0.0% | 3.8% | 20.3% | 75.9% | 100.0% |
| Total | | Count | 2 | 13 | 32 | 105 | 152 |
| | | Expected Count | 2.0 | 13.0 | 32.0 | 105.0 | 152.0 |

| | Do you have any previous experience with hydrogen cars (fuel cell vehicles)? I own/lease a hydrogen car | I have used a hydrogen car in the past | I know someone who has used a hydrogen car or know someone who has a hydrogen car | I have not used a hydrogen car and know no one who has | Total |
|---|---|---|---|---|---|
| % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 1.3% | 8.6% | 21.1% | 69.1% | 100.0% |

Each subscript letter denotes a subset of Do you have any previous experience with hydrogen cars (fuel cell vehicles)? categories whose column proportions do not differ significantly from each other at the .05 level.

Table B2.3.2. Chi-square results between participants' FCEV experience and willingness to purchase a FCEV.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 17.776[a] | 6 | .007 | .005 | | |
| Likelihood Ratio | 15.719 | 6 | .015 | .016 | | |
| Fisher-Freeman-Halton Exact Test | 14.395 | | | .011 | | |
| Linear-by-Linear Association | 12.333[b] | 1 | .000 | .000 | .000 | .000 |
| N of Valid Cases | 152 | | | | | |

a. 5 cells (41.7%) have expected count less than 5. The minimum expected count is .37.

b. The standardized statistic is 3.512.

Table B2.3.3. Measure of association between participants' FCEV experience and willingness to purchase a FCEV.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .342 | | | .007 | .005 |
| | Cramer's V | .242 | | | .007 | .005 |
| Interval by Interval | Pearson's R | .286 | .082 | 3.653 | .000[c] | .000 |
| Ordinal by Ordinal | Spearman Correlation | .231 | .082 | 2.910 | .004[c] | .004 |
| N of Valid Cases | | 152 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

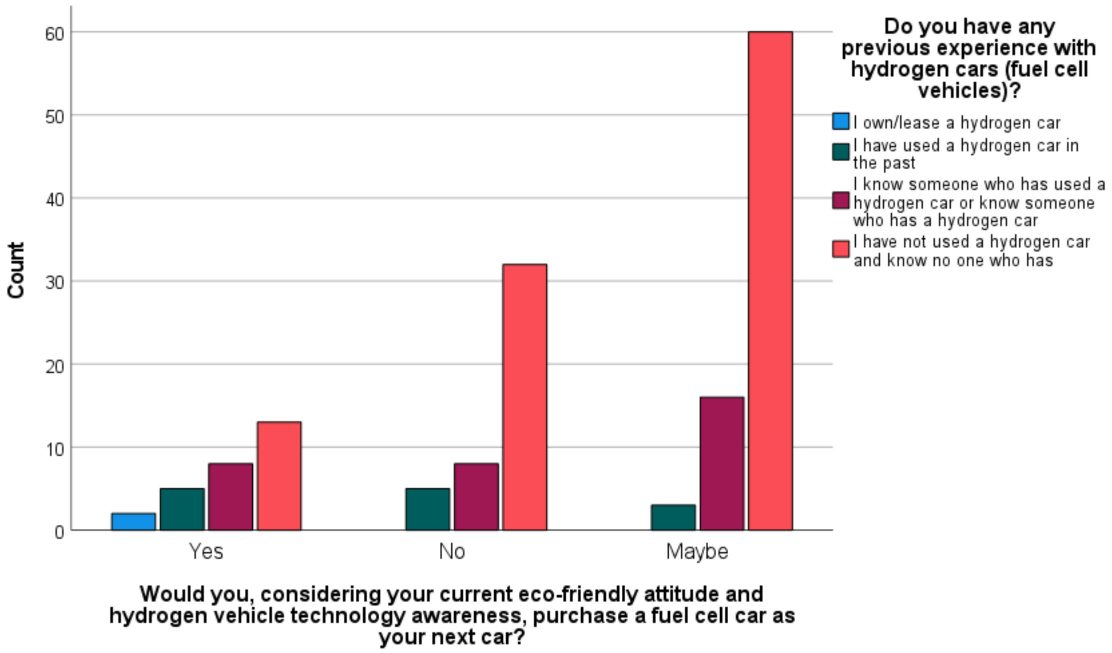



Fig. B2.3. Interaction between participants' FCEV experience and willingness to purchase a FCEV.

### *B2.4 Safety concerns*

Table B2.4.1. Crosstab statistic test between participants' safety concerns and willingness to purchase a FCEV.

| | | | Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is? | | | | |
|---|---|---|---|---|---|---|---|
| | | | Not safe | Less safe | The same | Safer | Total |
| Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | Yes | Count | $0_{a, b}$ | $3_{a, b}$ | $20_{b}$ | $5_{a}$ | 28 |
| | | Expected Count | .4 | 3.3 | 22.1 | 2.2 | 28.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 0.0% | 10.7% | 71.4% | 17.9% | 100.0% |
| | No | Count | $0_{a, b}$ | $10_{b}$ | $34_{a}$ | $2_{a}$ | 46 |
| | | Expected Count | .6 | 5.4 | 36.4 | 3.6 | 46.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 0.0% | 21.7% | 73.9% | 4.3% | 100.0% |
| | Maybe | Count | $2_{a}$ | $5_{b}$ | $67_{a}$ | $5_{a, b}$ | 79 |
| | | Expected Count | 1.0 | 9.3 | 62.5 | 6.2 | 79.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 2.5% | 6.3% | 84.8% | 6.3% | 100.0% |
| Total | | Count | 2 | 18 | 121 | 12 | 153 |
| | | Expected Count | 2.0 | 18.0 | 121.0 | 12.0 | 153.0 |

| | | Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is? | | | | |
|---|---|---|---|---|---|---|
| | | Not safe | Less safe | The same | Safer | Total |
| | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 1.3% | 11.8% | 79.1% | 7.8% | 100.0% |

Each subscript letter denotes a subset of Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is? categories whose column proportions do not differ significantly from each other at the .05 level.

Table B2.4.2. Chi-square results between participants' safety concerns and willingness to purchase a FCEV.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 12.992[a] | 6 | .043 | .038 | | |
| Likelihood Ratio | 12.580 | 6 | .050 | .063 | | |
| Fisher-Freeman-Halton Exact Test | 11.133 | | | .046 | | |
| Linear-by-Linear Association | .322[b] | 1 | .571 | .598 | .326 | .073 |
| N of Valid Cases | 153 | | | | | |

a. 6 cells (50.0%) have expected count less than 5. The minimum expected count is .37.

b. The standardized statistic is -.567.

Table B2.4.3. Measure of association between participants' safety concerns and willingness to purchase a FCEV.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .291 | | | .043 | .038 |
| | Cramer's V | .206 | | | .043 | .038 |
| Interval by Interval | Pearson's R | -.046 | .083 | -.566 | .572[c] | .598 |
| Ordinal by Ordinal | Spearman Correlation | .001 | .086 | .009 | .993[c] | .993 |
| N of Valid Cases | | 153 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

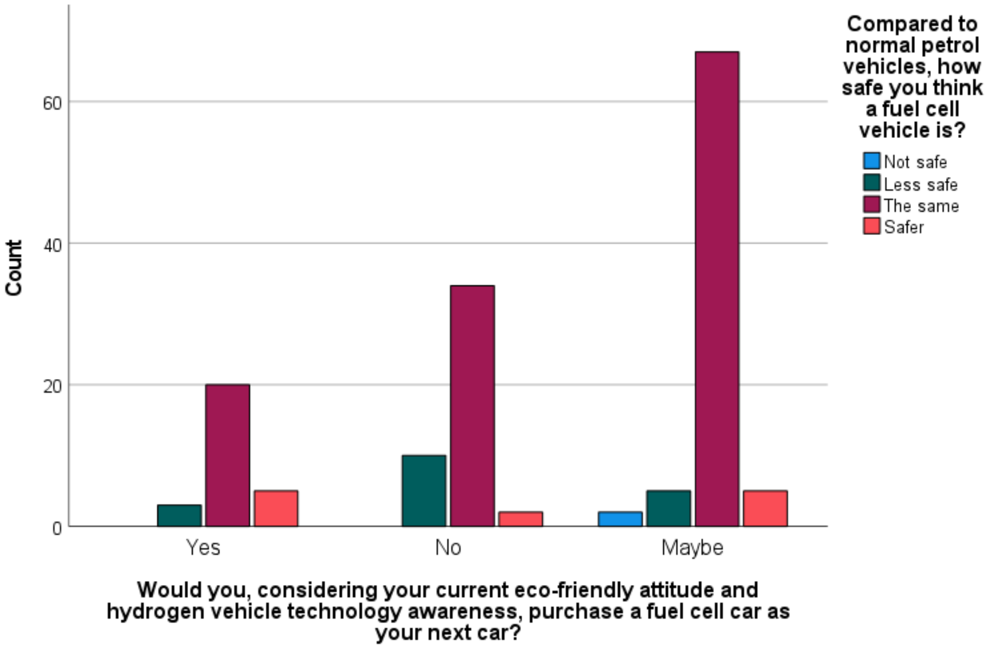



Fig. B2.4. Interaction between participants' safety concerns and willingness to purchase a FCEV.

*B2.5 Current hydrogen refuelling infrastructure*

Table B2.5.1. Crosstab statistic test between hydrogen refuelling infrastructure and willingness to purchase a FCEV.

| | | | There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | Yes | Count | $2_{a}$ | $0_{b}$ | $3_{b}$ | $23_{b}$ | 28 |
| | | Expected Count | .4 | 1.9 | 6.5 | 19.3 | 28.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 7.1% | 0.0% | 10.7% | 82.1% | 100.0% |
| | No | Count | $0_{a, b}$ | $6_{b}$ | $12_{a, b}$ | $27_{a}$ | 45 |
| | | Expected Count | .6 | 3.0 | 10.4 | 31.0 | 45.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 0.0% | 13.3% | 26.7% | 60.0% | 100.0% |
| | Maybe | Count | $0_{a}$ | $4_{a}$ | $20_{a}$ | $54_{a}$ | 78 |
| | | Expected Count | 1.0 | 5.2 | 18.1 | 53.7 | 78.0 |
| | | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 0.0% | 5.1% | 25.6% | 69.2% | 100.0% |
| Total | | Count | 2 | 10 | 35 | 104 | 151 |
| | | Expected Count | 2.0 | 10.0 | 35.0 | 104.0 | 151.0 |

| | | There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. | | | | |
|---|---|---|---|---|---|---|
| | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| | % within Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | 1.3% | 6.6% | 23.2% | 68.9% | 100.0% |

Each subscript letter denotes a subset of There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B2.5.2. Chi-square results between hydrogen refuelling infrastructure and willingness to purchase a FCEV.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 17.512[a] | 6 | .008 | .006 | | |
| Likelihood Ratio | 17.078 | 6 | .009 | .009 | | |
| Fisher-Freeman-Halton Exact Test | 13.203 | | | .018 | | |
| Linear-by-Linear Association | .035[b] | 1 | .851 | .876 | .451 | .060 |
| N of Valid Cases | 151 | | | | | |

a. 5 cells (41.7%) have expected count less than 5. The minimum expected count is .37.

b. The standardized statistic is .188.

Table B2.5.3. Measure of association between hydrogen refuelling infrastructure and willingness to purchase a FCEV.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .341 | | | .008 | .006 |
| | Cramer's V | .241 | | | .008 | .006 |
| Interval by Interval | Pearson's R | .015 | .087 | .187 | .852[c] | .876 |
| Ordinal by Ordinal | Spearman Correlation | -.022 | .079 | -.267 | .790[c] | .790 |
| N of Valid Cases | | 151 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

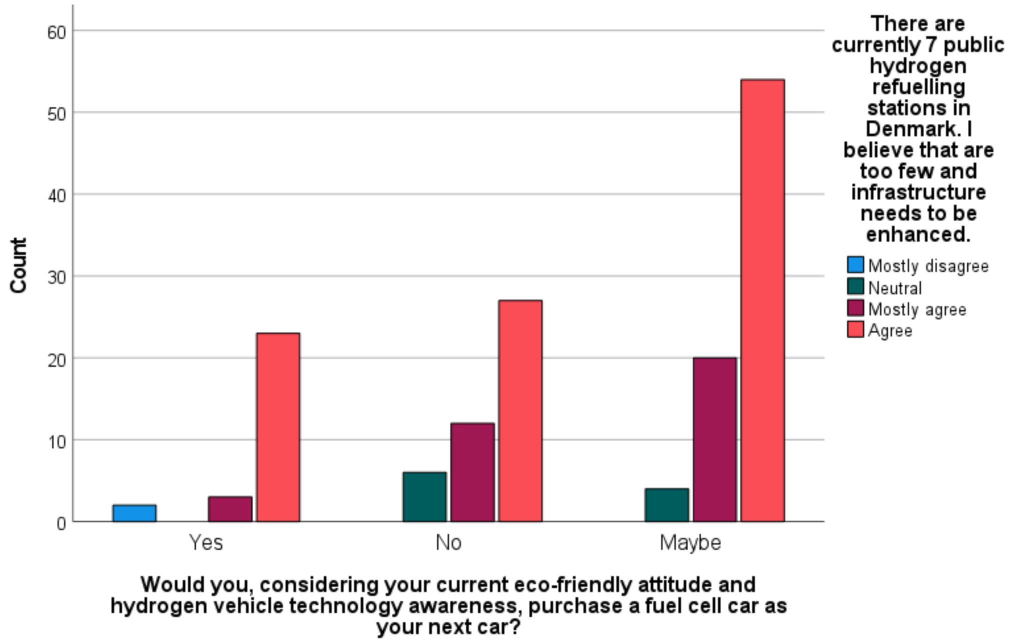



Fig. B2.5. Interaction between hydrogen refueling infrastructure and willingness to purchase a FCEV.

# B3 Prospects of the fuel cell electric vehicles market

## *B3.1 Willingness to purchase a FCEV*

Table B3.1.1. Crosstab statistic test between participants' willingness to purchase a FCEV and prospects of the FCEVs market.

| | | | Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? | | | |
|---|---|---|---|---|---|---|
| | | | Yes | No | Maybe | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $12_a$ | $1_b$ | $14_c$ | 27 |
| | | Expected Count | 4.8 | 8.0 | 14.1 | 27.0 |
| | | % within By taking into account all the above, I would... | 44.4% | 3.7% | 51.9% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $14_{a, b}$ | $16_b$ | $48_a$ | 78 |
| | | Expected Count | 13.9 | 23.2 | 40.8 | 78.0 |
| | | % within By taking into account all the above, I would... | 17.9% | 20.5% | 61.5% | 100.0% |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $1_a$ | $22_b$ | $14_a$ | 37 |
| | | Expected Count | 6.6 | 11.0 | 19.4 | 37.0 |
| | | % within By taking into account all the above, I would... | 2.7% | 59.5% | 37.8% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_a$ | $6_b$ | $3_a$ | 9 |
| | | Expected Count | 1.6 | 2.7 | 4.7 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 66.7% | 33.3% | 100.0% |
| Total | | Count | 27 | 45 | 79 | 151 |
| | | Expected Count | 27.0 | 45.0 | 79.0 | 151.0 |
| | | % within By taking into account all the above, I would... | 17.9% | 29.8% | 52.3% | 100.0% |

Each subscript letter denotes a subset of Would you, considering your current eco-friendly attitude and hydrogen vehicle technology awareness, purchase a fuel cell car as your next car? categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.1.2. Chi-square results between participants' willingness to purchase a FCEV and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 43.857[a] | 6 | .000 | .000 | | |
| Likelihood Ratio | 45.667 | 6 | .000 | .000 | | |
| Fisher-Freeman-Halton Exact Test | 41.230 | | | .000 | | |
| Linear-by-Linear Association | .972[b] | 1 | .324 | .350 | .180 | .033 |
| N of Valid Cases | 151 | | | | | |

a. 4 cells (33.3%) have expected count less than 5. The minimum expected count is 1.61.

b. The standardized statistic is .986.

Table B3.1.3. Measure of association between participants' willingness to purchase a FCEV and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .539 | | | .000 | .000 |
| | Cramer's V | .381 | | | .000 | .000 |
| Interval by Interval | Pearson's R | .081 | .078 | .986 | .326[c] | .350 |
| Ordinal by Ordinal | Spearman Correlation | .011 | .088 | .134 | .893[c] | .893 |
| N of Valid Cases | | 151 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

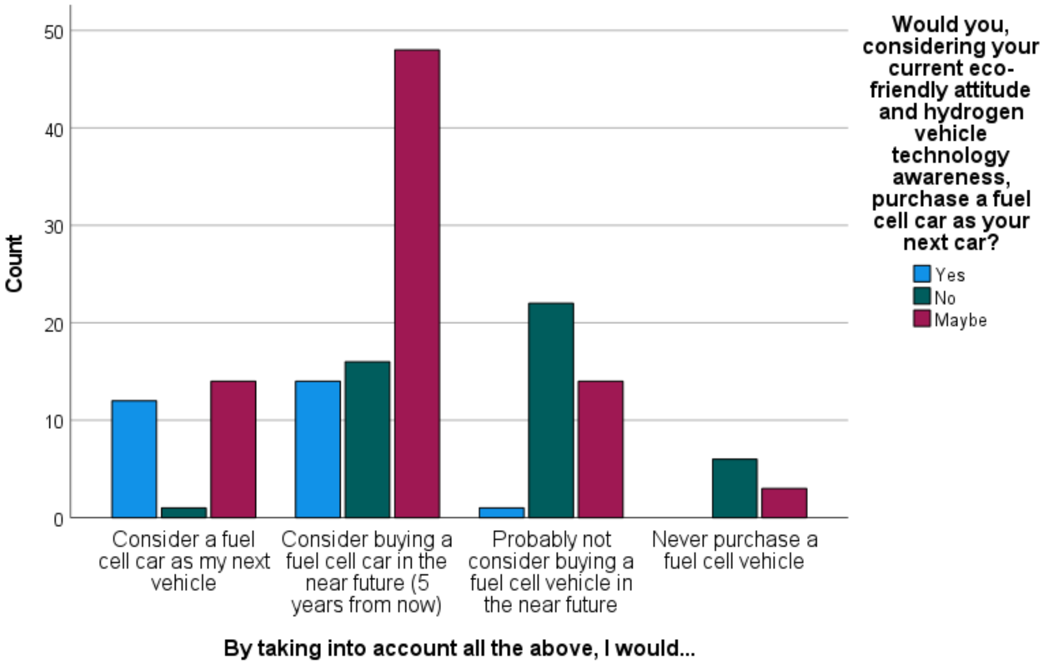



Fig. B3.1. Interaction between participants' willingness to purchase a FCEV and prospects of the FCEVs market.

### *B3.2 FCEV price*

Table B3.2.1. Crosstab statistic test between FCEV price and prospects of the FCEVs market.

| | | | The price of a hydrogen car is currently 515,000-583,000 DKK. I think that it is too expensive. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $0_a$ | $1_a$ | $12_a$ | $14_a$ | 27 |
| | | Expected Count | .9 | 2.1 | 7.3 | 16.6 | 27.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 3.7% | 44.4% | 51.9% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $2_a$ | $6_a$ | $22_a$ | $49_a$ | 79 |
| | | Expected Count | 2.6 | 6.3 | 21.5 | 48.7 | 79.0 |
| | | % within By taking into account all the above, I would... | 2.5% | 7.6% | 27.8% | 62.0% | 100.0% |
| | | Count | $3_a$ | $2_{a, b}$ | $7_b$ | $24_{a, b}$ | 36 |

| | | | The price of a hydrogen car is currently 515,000-583,000 DKK. I think that it is too expensive. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| | Probably not consider buying a fuel cell vehicle in the near future | Expected Count | 1.2 | 2.9 | 9.8 | 22.2 | 36.0 |
| | | % within By taking into account all the above, I would... | 8.3% | 5.6% | 19.4% | 66.7% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_{a, b}$ | $3_{b}$ | $0_{a}$ | $6_{a}$ | 9 |
| | | Expected Count | .3 | .7 | 2.4 | 5.5 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 33.3% | 0.0% | 66.7% | 100.0% |
| Total | | Count | 5 | 12 | 41 | 93 | 151 |
| | | Expected Count | 5.0 | 12.0 | 41.0 | 93.0 | 151.0 |
| | | % within By taking into account all the above, I would... | 3.3% | 7.9% | 27.2% | 61.6% | 100.0% |

Each subscript letter denotes a subset of The price of a hydrogen car is currently 515,000-583,000 DKK. I think that it is too expensive. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.2.2. Chi-square results between FCEV price and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 19.086[a] | 9 | .024 | .028 | | |
| Likelihood Ratio | 18.454 | 9 | .030 | .038 | | |
| Fisher-Freeman-Halton Exact Test | 14.947 | | | .051 | | |
| Linear-by-Linear Association | .237[b] | 1 | .626 | .646 | .335 | .046 |
| N of Valid Cases | 151 | | | | | |

a. 8 cells (50.0%) have expected count less than 5. The minimum expected count is .30.

b. The standardized statistic is -.487.

Table B3.2.3. Measure of association between FCEV price and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .356 | | | .024 | .028 |
| | Cramer's V | .205 | | | .024 | .028 |
| Interval by Interval | Pearson's R | -.040 | .083 | -.486 | .628[c] | .646 |
| Ordinal by Ordinal | Spearman Correlation | .041 | .084 | .497 | .620[c] | .620 |
| N of Valid Cases | | 151 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

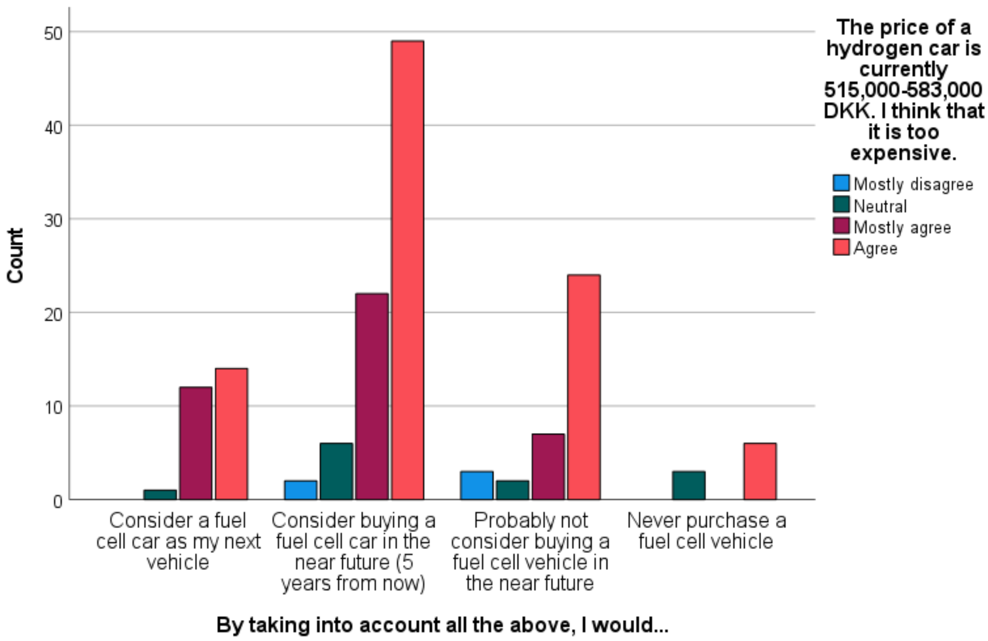



Fig. B3.2. Interaction between FCEV price and prospects of the FCEVs market.

### *B3.3 Current hydrogen fuel price*

Table B3.3.1. Crosstab statistic test between current hydrogen fuel price and prospects of the FCEVs market.

| | | | I believe that the fuel cost of hydrogen cars needs to be reduced more. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $1_a$ | $4_a$ | $8_a$ | $14_a$ | 27 |
| | | Expected Count | .9 | 5.2 | 5.5 | 15.5 | 27.0 |
| | | % within By taking into account all the above, I would... | 3.7% | 14.8% | 29.6% | 51.9% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $3_a$ | $12_a$ | $13_a$ | $51_a$ | 79 |
| | | Expected Count | 2.6 | 15.1 | 16.1 | 45.2 | 79.0 |
| | | % within By taking into account all the above, I would... | 3.8% | 15.2% | 16.5% | 64.6% | 100.0% |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $1_a$ | $10_a$ | $10_a$ | $16_a$ | 37 |
| | | Expected Count | 1.2 | 7.1 | 7.5 | 21.2 | 37.0 |
| | | % within By taking into account all the above, I would... | 2.7% | 27.0% | 27.0% | 43.2% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_a$ | $3_a$ | $0_a$ | $6_a$ | 9 |
| | | Expected Count | .3 | 1.7 | 1.8 | 5.2 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 33.3% | 0.0% | 66.7% | 100.0% |
| Total | | Count | 5 | 29 | 31 | 87 | 152 |
| | | Expected Count | 5.0 | 29.0 | 31.0 | 87.0 | 152.0 |
| | | % within By taking into account all the above, I would... | 3.3% | 19.1% | 20.4% | 57.2% | 100.0% |

Each subscript letter denotes a subset of I believe that the fuel cost of hydrogen cars needs to be reduced more. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.3.2. Chi-square results between current hydrogen fuel price and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 10.124[a] | 9 | .341 | .331 | | |
| Likelihood Ratio | 11.919 | 9 | .218 | .274 | | |
| Fisher-Freeman-Halton Exact Test | 10.213 | | | .273 | | |
| Linear-by-Linear Association | .617[b] | 1 | .432 | .457 | .233 | .033 |
| N of Valid Cases | 152 | | | | | |

a. 6 cells (37.5%) have expected count less than 5. The minimum expected count is .30.

b. The standardized statistic is -.785.

### *B3.4 Individuals' net income*

Table B3.4.1. Crosstab statistic test between participants' net income and prospects of the FCEVs market.

| | | | Net annual income in DKK (comma separator depicts thousands) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 0 - 200,000 | 200,001 - 300,000 | 300,001 - 400,000 | 400,000 - 500,000 | 500,001 - 600,000 | 600,001 or more | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $4_a$ | $7_a$ | $4_a$ | $4_a$ | $2_a$ | $6_a$ | 27 |
| | | Expected Count | 6.1 | 5.0 | 5.0 | 4.6 | 2.7 | 3.6 | 27.0 |
| | | % within By taking into account all the above, I would... | 14.8% | 25.9% | 14.8% | 14.8% | 7.4% | 22.2% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $14_a$ | $15_a$ | $13_a$ | $16_a$ | $10_a$ | $10_a$ | 78 |
| | | Expected Count | 17.6 | 14.5 | 14.5 | 13.4 | 7.7 | 10.3 | 78.0 |
| | | % within By taking into account all the above, I would... | 17.9% | 19.2% | 16.7% | 20.5% | 12.8% | 12.8% | 100.0% |

| | | | Net annual income in DKK (comma separator depicts thousands) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 0 - 200,000 | 200,001 - 300,000 | 300,001 - 400,000 | 400,000 - 500,000 | 500,001 - 600,000 | 600,001 or more | Total |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $13_{a}$ | $6_{a, b}$ | $9_{a}$ | $2_{b}$ | $3_{a, b}$ | $4_{a, b}$ | 37 |
| | | Expected Count | 8.3 | 6.9 | 6.9 | 6.4 | 3.7 | 4.9 | 37.0 |
| | | % within By taking into account all the above, I would... | 35.1% | 16.2% | 24.3% | 5.4% | 8.1% | 10.8% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $3_{a, b}$ | $0_{b}$ | $2_{a, b}$ | $4_{a}$ | $0_{a, b}$ | $0_{a, b}$ | 9 |
| | | Expected Count | 2.0 | 1.7 | 1.7 | 1.5 | .9 | 1.2 | 9.0 |
| | | % within By taking into account all the above, I would... | 33.3% | 0.0% | 22.2% | 44.4% | 0.0% | 0.0% | 100.0% |
| Total | | Count | 34 | 28 | 28 | 26 | 15 | 20 | 151 |
| | | Expected Count | 34.0 | 28.0 | 28.0 | 26.0 | 15.0 | 20.0 | 151.0 |
| | | % within By taking into account all the above, I would... | 22.5% | 18.5% | 18.5% | 17.2% | 9.9% | 13.2% | 100.0% |

Each subscript letter denotes a subset of Net annual income in DKK (comma separator depicts thousands) categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.4.2. Chi-square results between participants' net income and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Monte Carlo Sig. (2-sided) Significance | Monte Carlo Sig. (2-sided) 99% Confidence Interval Lower Bound | Monte Carlo Sig. (2-sided) 99% Confidence Interval Upper Bound | Monte Carlo Sig. (1-sided) Significance | Monte Carlo Sig. (1-sided) 99% Confidence Interval Lower Bound | Monte Carlo Sig. (1-sided) 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|---|
| Pearson Chi-Square | 20.504[a] | 15 | .153 | .150[b] | .141 | .159 | | | |
| Likelihood Ratio | 23.434 | 15 | .075 | .119[b] | .111 | .127 | | | |
| Fisher-Freeman-Halton Exact Test | 18.434 | | | .183[b] | .173 | .193 | | | |
| Linear-by-Linear Association | 3.491[c] | 1 | .062 | .061[b] | .055 | .067 | .033[b] | .028 | .037 |
| N of Valid Cases | 151 | | | | | | | | |

a. 11 cells (45.8%) have expected count less than 5. The minimum expected count is .89.

b. Based on 10000 sampled tables with starting seed 2000000.

c. The standardized statistic is -1.868.

## *B3.5 Current hydrogen refuelling infrastructure*

Table B3.5.1. Crosstab statistic test between hydrogen refuelling infrastructure and prospects of the FCEVs market.

| | | | There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. Mostly disagree | Neutral | Mostly agree | Agree | Total |
|---|---|---|---|---|---|---|---|
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $0_a$ | $0_a$ | $6_a$ | $21_a$ | 27 |
| | | Expected Count | .4 | 1.8 | 6.4 | 18.5 | 27.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 0.0% | 22.2% | 77.8% | 100.0% |
| | Consider buying a fuel cell car in the | Count | $2_a$ | $2_b$ | $15_{a, b}$ | $60_a$ | 79 |
| | | Expected Count | 1.0 | 5.2 | 18.7 | 54.1 | 79.0 |

| | | | There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| | near future (5 years from now) | % within By taking into account all the above, I would... | 2.5% | 2.5% | 19.0% | 75.9% | 100.0% |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $0_{a, b}$ | $7_{b}$ | $14_{b}$ | $16_{a}$ | 37 |
| | | Expected Count | .5 | 2.4 | 8.8 | 25.3 | 37.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 18.9% | 37.8% | 43.2% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_{a}$ | $1_{a}$ | $1_{a}$ | $7_{a}$ | 9 |
| | | Expected Count | .1 | .6 | 2.1 | 6.2 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 11.1% | 11.1% | 77.8% | 100.0% |
| Total | | Count | 2 | 10 | 36 | 104 | 152 |
| | | Expected Count | 2.0 | 10.0 | 36.0 | 104.0 | 152.0 |
| | | % within By taking into account all the above, I would... | 1.3% | 6.6% | 23.7% | 68.4% | 100.0% |

Each subscript letter denotes a subset of There are currently 7 public hydrogen refuelling stations in Denmark. I believe that are too few and infrastructure needs to be enhanced. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.5.2. Chi-square results between hydrogen refuelling infrastructure and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 23.470[a] | 9 | .005 | .009 | | |
| Likelihood Ratio | 23.864 | 9 | .005 | .003 | | |
| Fisher-Freeman-Halton Exact Test | 20.908 | | | .004 | | |
| Linear-by-Linear Association | 6.369[b] | 1 | .012 | .012 | .008 | .003 |
| N of Valid Cases | 152 | | | | | |

a. 8 cells (50.0%) have expected count less than 5. The minimum expected count is .12.

b. The standardized statistic is -2.524.

Table B3.5.3. Measure of association between hydrogen refuelling infrastructure and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .393 | | | .005 | .009 |
| | Cramer's V | .227 | | | .005 | .009 |
| Interval by Interval | Pearson's R | -.205 | .074 | -2.570 | .011[c] | .012 |
| Ordinal by Ordinal | Spearman Correlation | -.233 | .079 | -2.928 | .004[c] | .004 |
| N of Valid Cases | | 152 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

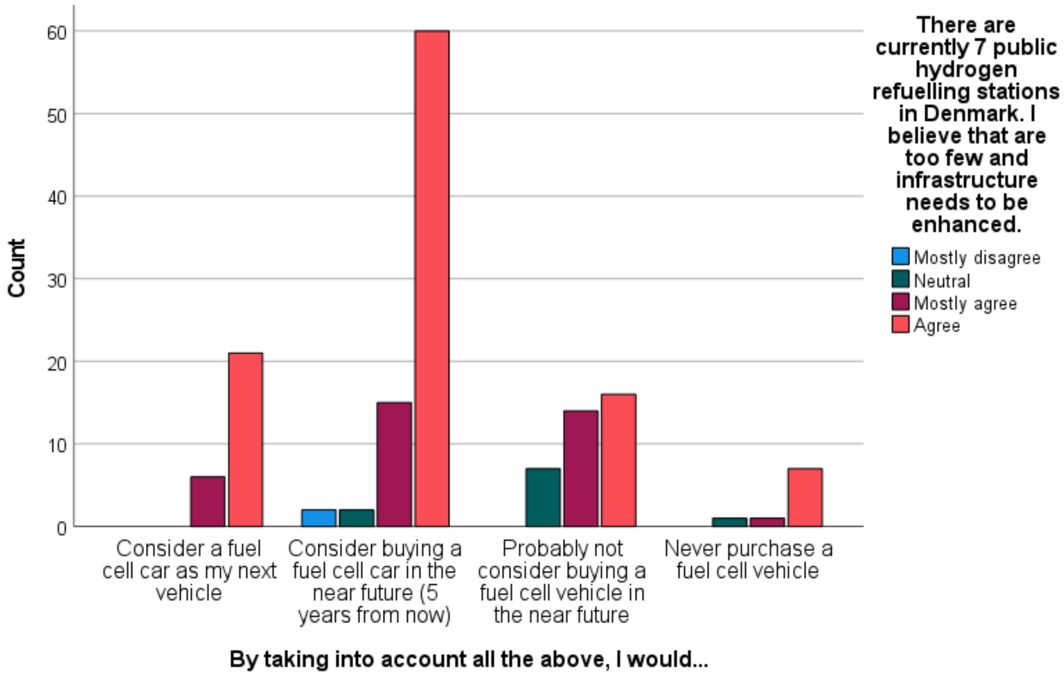



Fig. B3.5. Interaction between hydrogen refuelling infrastructure and prospects of the FCEVs market.

### *B3.6 Safety concerns*

Table B3.6.1. Crosstab statistic test between participants' safety concerns and prospects of the FCEVs market.

| | | | Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is? | | | | |
|---|---|---|---|---|---|---|---|
| | | | Not safe | Less safe | The same | Safer | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $0_a$ | $3_a$ | $20_a$ | $4_a$ | 27 |
| | | Expected Count | .4 | 3.0 | 21.5 | 2.1 | 27.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 11.1% | 74.1% | 14.8% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $2_a$ | $4_b$ | $66_a$ | $7_{a, b}$ | 79 |
| | | Expected Count | 1.0 | 8.8 | 62.9 | 6.2 | 79.0 |
| | | % within By taking into account all the above, I would... | 2.5% | 5.1% | 83.5% | 8.9% | 100.0% |
| | | Count | $0_a$ | $6_a$ | $30_a$ | $1_a$ | 37 |
| | | Expected Count | .5 | 4.1 | 29.5 | 2.9 | 37.0 |

| | | | Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is? | | | | |
|---|---|---|---|---|---|---|---|
| | | | Not safe | Less safe | The same | Safer | Total |
| | Probably not consider buying a fuel cell vehicle in the near future | % within By taking into account all the above, I would... | 0.0% | 16.2% | 81.1% | 2.7% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_{a, b}$ | $4_{b}$ | $5_{a}$ | $0_{a, b}$ | 9 |
| | | Expected Count | .1 | 1.0 | 7.2 | .7 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 44.4% | 55.6% | 0.0% | 100.0% |
| Total | | Count | 2 | 17 | 121 | 12 | 152 |
| | | Expected Count | 2.0 | 17.0 | 121.0 | 12.0 | 152.0 |
| | | % within By taking into account all the above, I would... | 1.3% | 11.2% | 79.6% | 7.9% | 100.0% |

Each subscript letter denotes a subset of Compared to normal petrol vehicles, how safe you think a fuel cell vehicle is? categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.6.2. Chi-square results between participants' safety concerns and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 18.861[a] | 9 | .026 | .030 | | |
| Likelihood Ratio | 17.242 | 9 | .045 | .043 | | |
| Fisher-Freeman-Halton Exact Test | 15.423 | | | .036 | | |
| Linear-by-Linear Association | 6.650[b] | 1 | .010 | .012 | .007 | .003 |
| N of Valid Cases | 152 | | | | | |

a. 10 cells (62.5%) have expected count less than 5. The minimum expected count is .12.

b. The standardized statistic is -2.579.

Table B3.6.3. Measure of association between participants' safety concerns and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .352 | | | .026 | .030 |
| | Cramer's V | .203 | | | .026 | .030 |
| Interval by Interval | Pearson's R | -.210 | .081 | -2.629 | .009[c] | .012 |
| Ordinal by Ordinal | Spearman Correlation | -.215 | .083 | -2.702 | .008[c] | .008 |
| N of Valid Cases | | 152 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

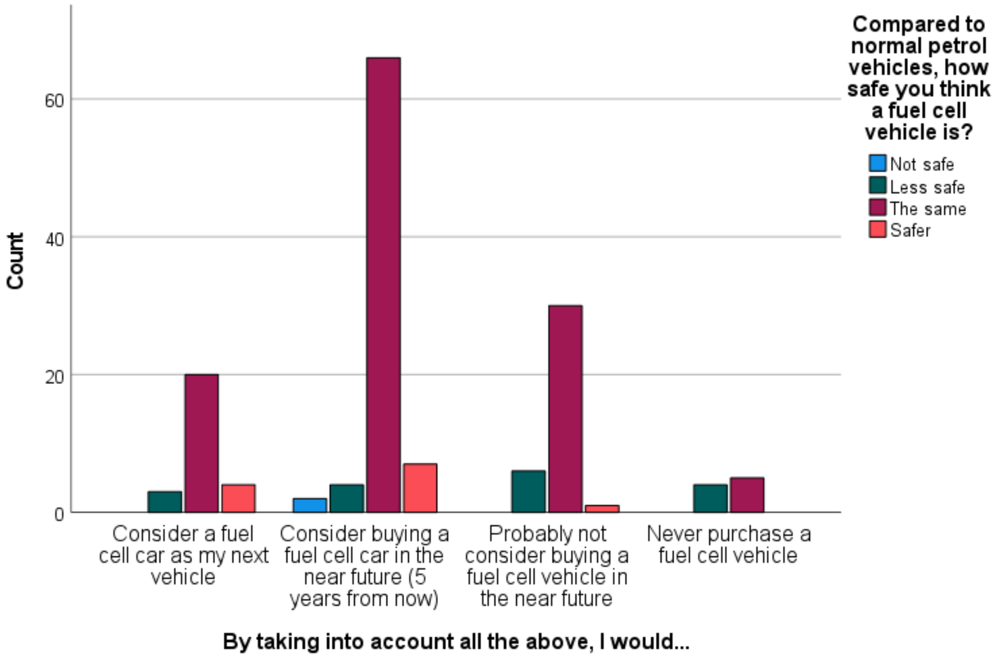



Fig. B3.6. Interaction between participants' safety concerns and prospects of the FCEVs market.

### *B3.7 Media orientation*

Table B3.7.1. Crosstab statistic test between media orientation and prospects of the FCEVs market.

| | | | The public media must focus more on hydrogen cars. | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Disagree | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $0_{a, b}$ | $0_{a, b}$ | $3_{b}$ | $4_{a, b}$ | $20_{a}$ | 27 |
| | | Expected Count | .4 | 1.8 | 6.1 | 5.8 | 13.0 | 27.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 0.0% | 11.1% | 14.8% | 74.1% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $0_{a, b, c}$ | $3_{b, c}$ | $9_{c}$ | $19_{a, b}$ | $48_{a}$ | 79 |
| | | Expected Count | 1.0 | 5.1 | 18.0 | 16.9 | 38.0 | 79.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 3.8% | 11.4% | 24.1% | 60.8% | 100.0% |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $1_{a, b}$ | $5_{a, b}$ | $18_{b}$ | $8_{a}$ | $6_{c}$ | 38 |
| | | Expected Count | .5 | 2.5 | 8.6 | 8.1 | 18.3 | 38.0 |
| | | % within By taking into account all the above, I would... | 2.6% | 13.2% | 47.4% | 21.1% | 15.8% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $1_{a}$ | $2_{a, b}$ | $5_{a, b}$ | $2_{b}$ | $0_{c}$ | 10 |
| | | Expected Count | .1 | .6 | 2.3 | 2.1 | 4.8 | 10.0 |
| | | % within By taking into account all the above, I would... | 10.0% | 20.0% | 50.0% | 20.0% | 0.0% | 100.0% |
| Total | | Count | 2 | 10 | 35 | 33 | 74 | 154 |
| | | Expected Count | 2.0 | 10.0 | 35.0 | 33.0 | 74.0 | 154.0 |
| | | % within By taking into account all the above, I would... | 1.3% | 6.5% | 22.7% | 21.4% | 48.1% | 100.0% |

Each subscript letter denotes a subset of The public media must focus more on hydrogen cars. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.7.2. Chi-square results between media orientation and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Monte Carlo Sig. (2-sided) Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound | Monte Carlo Sig. (1-sided) Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|---|
| Pearson Chi-Square | 55.579[a] | 12 | .000 | .000[b] | .000 | .000 | | | |
| Likelihood Ratio | 58.792 | 12 | .000 | .000[b] | .000 | .000 | | | |
| Fisher-Freeman-Halton Exact Test | 54.370 | | | .000[b] | .000 | .000 | | | |
| Linear-by-Linear Association | 43.966[c] | 1 | .000 | .000[b] | .000 | .000 | .000[b] | .000 | .000 |
| N of Valid Cases | 154 | | | | | | | | |

a. 10 cells (50.0%) have expected count less than 5. The minimum expected count is .13.

b. Based on 10000 sampled tables with starting seed 743671174.

c. The standardized statistic is -6.631.

Table B3.7.3. Measure of association between media orientation and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Monte Carlo Significance Significance | 99% Confidence Interval Lower Bound | 99% Confidence Interval Upper Bound |
|---|---|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .601 | | | .000 | .000[c] | .000 | .000 |
| | Cramer's V | .347 | | | .000 | .000[c] | .000 | .000 |
| Interval by Interval | Pearson's R | -.536 | .057 | -7.829 | .000[d] | .000[c] | .000 | .000 |
| Ordinal by Ordinal | Spearman Correlation | -.533 | .061 | -7.769 | .000[d] | .000[c] | .000 | .000 |
| N of Valid Cases | | 154 | | | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on 10000 sampled tables with starting seed 743671174.

d. Based on normal approximation.

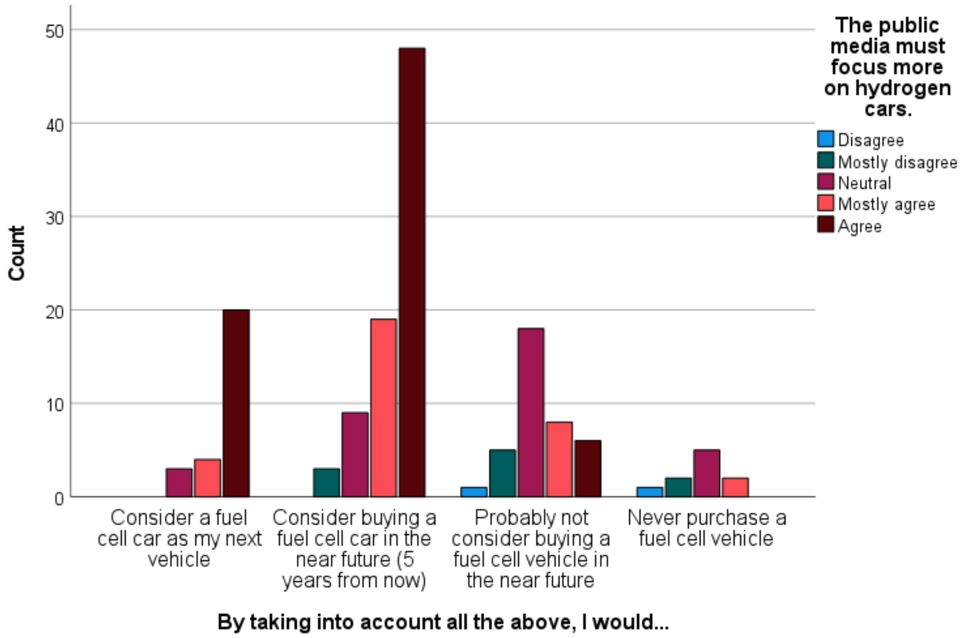



Fig. B3.7. Interaction between media orientation and prospects of the FCEVs market.

## *B3.8 Future FCEVs price*

Table B3.8.1. Crosstab statistic test between future FCEVs price and prospects of the FCEVs market.

| | | | If the price of a hydrogen car would drop by 50% in the future, the hydrogen car market would be highly competitive. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $2_{a}$ | $0_{b}$ | $6_{a, b}$ | $19_{a}$ | 27 |
| | | Expected Count | 1.1 | 2.7 | 8.0 | 15.2 | 27.0 |
| | | % within By taking into account all the above, I would... | 7.4% | 0.0% | 22.2% | 70.4% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $2_{a, b}$ | $1_{b}$ | $21_{a}$ | $54_{a}$ | 78 |
| | | Expected Count | 3.1 | 7.7 | 23.2 | 43.9 | 78.0 |
| | | % within By taking into account all the above, I would... | 2.6% | 1.3% | 26.9% | 69.2% | 100.0% |

| | | | If the price of a hydrogen car would drop by 50% in the future, the hydrogen car market would be highly competitive. | | | | |
|---|---|---|---|---|---|---|---|
| | | | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $2_{a, b}$ | $12_{c}$ | $13_{b}$ | $10_{a}$ | 37 |
| | | Expected Count | 1.5 | 3.7 | 11.0 | 20.8 | 37.0 |
| | | % within By taking into account all the above, I would... | 5.4% | 32.4% | 35.1% | 27.0% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_{a, b}$ | $2_{b}$ | $5_{b}$ | $2_{a}$ | 9 |
| | | Expected Count | .4 | .9 | 2.7 | 5.1 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 22.2% | 55.6% | 22.2% | 100.0% |
| Total | | Count | 6 | 15 | 45 | 85 | 151 |
| | | Expected Count | 6.0 | 15.0 | 45.0 | 85.0 | 151.0 |
| | | % within By taking into account all the above, I would... | 4.0% | 9.9% | 29.8% | 56.3% | 100.0% |

Each subscript letter denotes a subset of If the price of a hydrogen car would drop by 50% in the future, the hydrogen car market would be highly competitive. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.8.2. Chi-square results between future FCEVs price and prospects of the FCEVs market.

| | Value | df | Asymptotic Significance (2-sided) | Exact Sig. (2-sided) | Exact Sig. (1-sided) | Point Probability |
|---|---|---|---|---|---|---|
| Pearson Chi-Square | 44.370[a] | 9 | .000 | .000 | | |
| Likelihood Ratio | 44.651 | 9 | .000 | .000 | | |
| Fisher-Freeman-Halton Exact Test | 41.235 | | | .000 | | |
| Linear-by-Linear Association | 15.684[b] | 1 | .000 | .000 | .000 | .000 |
| N of Valid Cases | 151 | | | | | |

a. 8 cells (50.0%) have expected count less than 5. The minimum expected count is .36.

b. The standardized statistic is -3.960.

Table B3.8.3. Measure of association between future FCEVs price and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Exact Significance |
|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .542 | | | .000 | .000 |
| | Cramer's V | .313 | | | .000 | .000 |
| Interval by Interval | Pearson's R | -.323 | .083 | -4.171 | .000[c] | .000 |
| Ordinal by Ordinal | Spearman Correlation | -.379 | .077 | -4.996 | .000[c] | .000 |
| N of Valid Cases | | 151 | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on normal approximation.

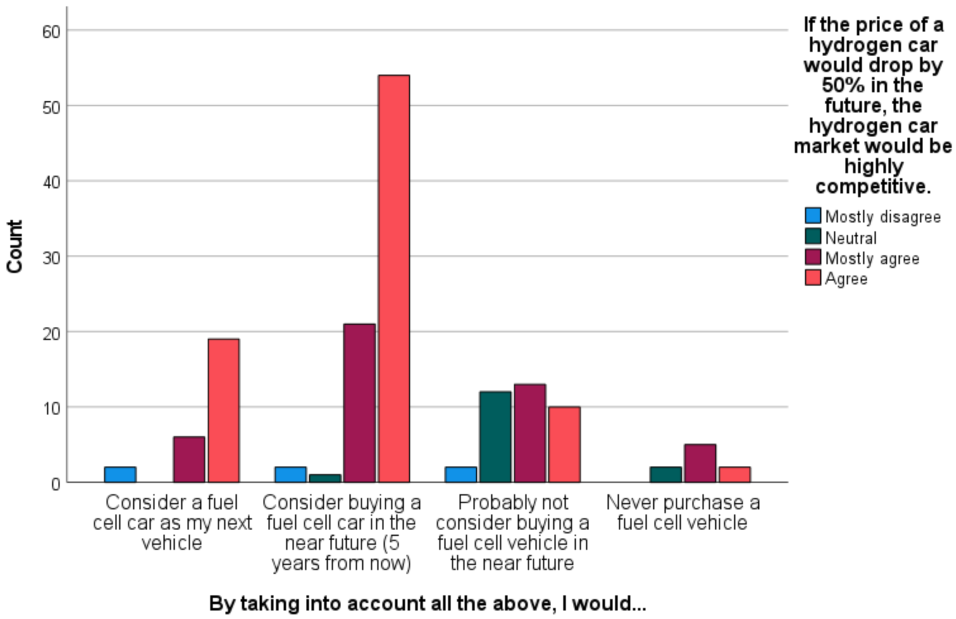



Fig. B3.8. Interaction between future FCEVs price and prospects of the FCEVs market.

### *B3.9 Future hydrogen fuel price*

Table B3.9.1. Crosstab statistic test between future hydrogen fuel price and prospects of the FCEVs market.

| | | | If the hydrogen fuel price would decrease by 30% in the future (without a decrease of the vehicle's price), hydrogen cars would be more competitive. | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Disagree | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| By taking into account all the above, I would... | Consider a fuel cell car as my next vehicle | Count | $0_{a}$ | $2_{a}$ | $7_{a}$ | $11_{a}$ | $7_{a}$ | 27 |
| | | Expected Count | .5 | 3.6 | 8.6 | 7.0 | 7.3 | 27.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 7.4% | 25.9% | 40.7% | 25.9% | 100.0% |
| | Consider buying a fuel cell car in the near future (5 years from now) | Count | $3_{a}$ | $6_{b}$ | $20_{b, c}$ | $23_{a, c}$ | $26_{a}$ | 78 |
| | | Expected Count | 1.5 | 10.3 | 24.8 | 20.1 | 21.2 | 78.0 |
| | | % within By taking into account all the above, I would... | 3.8% | 7.7% | 25.6% | 29.5% | 33.3% | 100.0% |
| | Probably not consider buying a fuel cell vehicle in the near future | Count | $0_{a, b, c}$ | $12_{c}$ | $15_{b}$ | $5_{a}$ | $5_{a}$ | 37 |
| | | Expected Count | .7 | 4.9 | 11.8 | 9.6 | 10.0 | 37.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 32.4% | 40.5% | 13.5% | 13.5% | 100.0% |
| | Never purchase a fuel cell vehicle | Count | $0_{a, b}$ | $0_{a, b}$ | $6_{b}$ | $0_{a}$ | $3_{a, b}$ | 9 |
| | | Expected Count | .2 | 1.2 | 2.9 | 2.3 | 2.4 | 9.0 |
| | | % within By taking into account all the above, I would... | 0.0% | 0.0% | 66.7% | 0.0% | 33.3% | 100.0% |
| Total | | Count | 3 | 20 | 48 | 39 | 41 | 151 |
| | | Expected Count | 3.0 | 20.0 | 48.0 | 39.0 | 41.0 | 151.0 |

| | | If the hydrogen fuel price would decrease by 30% in the future (without a decrease of the vehicle's price), hydrogen cars would be more competitive. | | | | | |
|---|---|---|---|---|---|---|---|
| | | Disagree | Mostly disagree | Neutral | Mostly agree | Agree | Total |
| | % within By taking into account all the above, I would... | 2.0% | 13.2% | 31.8% | 25.8% | 27.2% | 100.0% |

Each subscript letter denotes a subset of If the hydrogen fuel price would decrease by 30% in the future (without a decrease of the vehicle's price), hydrogen cars would be more competitive. categories whose column proportions do not differ significantly from each other at the .05 level.

Table B3.9.2. Chi-square results between future hydrogen fuel price and prospects of the FCEVs market.

| | | | | Monte Carlo Sig. (2-sided) | | | Monte Carlo Sig. (1-sided) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 99% Confidence Interval | | | 99% Confidence Interval | |
| | Value | df | Asymptotic Significance (2-sided) | Significance | Lower Bound | Upper Bound | Significance | Lower Bound | Upper Bound |
| Pearson Chi-Square | 33.350[a] | 12 | .001 | .002[b] | .001 | .003 | | | |
| Likelihood Ratio | 35.260 | 12 | .000 | .001[b] | .000 | .001 | | | |
| Fisher-Freeman-Halton Exact Test | 28.626 | | | .001[b] | .000 | .002 | | | |
| Linear-by-Linear Association | 5.925[c] | 1 | .015 | .015[b] | .012 | .018 | .008[b] | .006 | .011 |
| N of Valid Cases | 151 | | | | | | | | |

a. 10 cells (50.0%) have expected count less than 5. The minimum expected count is .18.

b. Based on 10000 sampled tables with starting seed 329836257.

c. The standardized statistic is -2.434.

Table B3.9.3. Measure of association between future hydrogen fuel price and prospects of the FCEVs market.

| | | Value | Asymptotic Standard Error[a] | Approximate T[b] | Approximate Significance | Monte Carlo Significance: Significance | 99% Confidence Interval: Lower Bound | 99% Confidence Interval: Upper Bound |
|---|---|---|---|---|---|---|---|---|
| Nominal by Nominal | Phi | .470 | | | .001 | .002[c] | .001 | .003 |
| | Cramer's V | .271 | | | .001 | .002[c] | .001 | .003 |
| Interval by Interval | Pearson's R | -.199 | .074 | -2.475 | .014[d] | .015[c] | .012 | .018 |
| Ordinal by Ordinal | Spearman Correlation | -.236 | .076 | -2.967 | .003[d] | .004[c] | .003 | .006 |
| N of Valid Cases | | 151 | | | | | | |

a. Not assuming the null hypothesis.

b. Using the asymptotic standard error assuming the null hypothesis.

c. Based on 10000 sampled tables with starting seed 329836257.

d. Based on normal approximation.

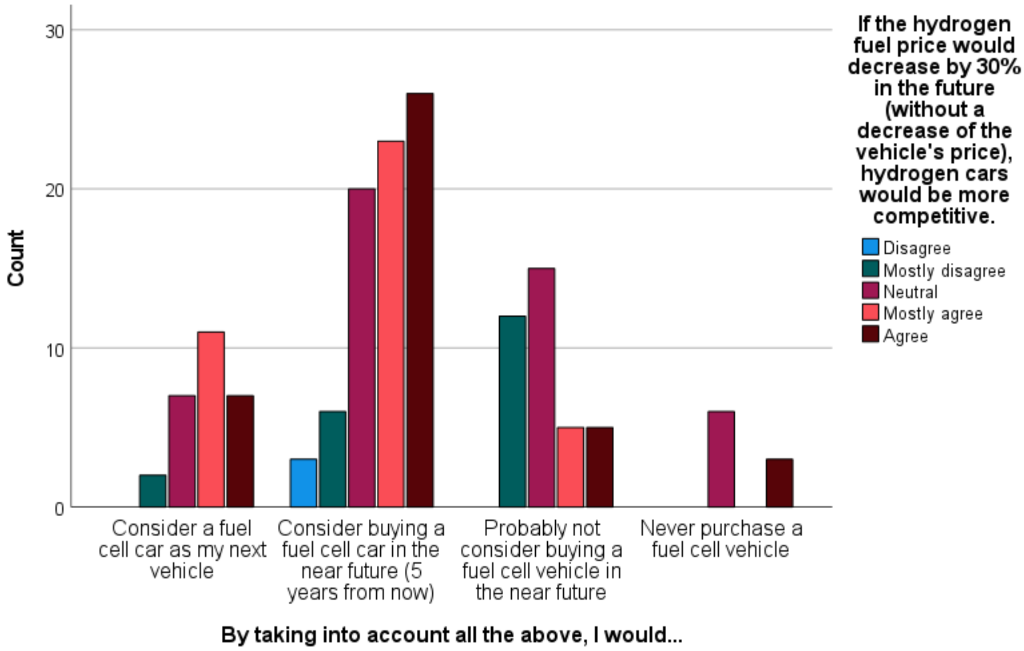



Fig. B3.9. Interaction between future hydrogen fuel price and prospects of the FCEVs market.

# Appendix C

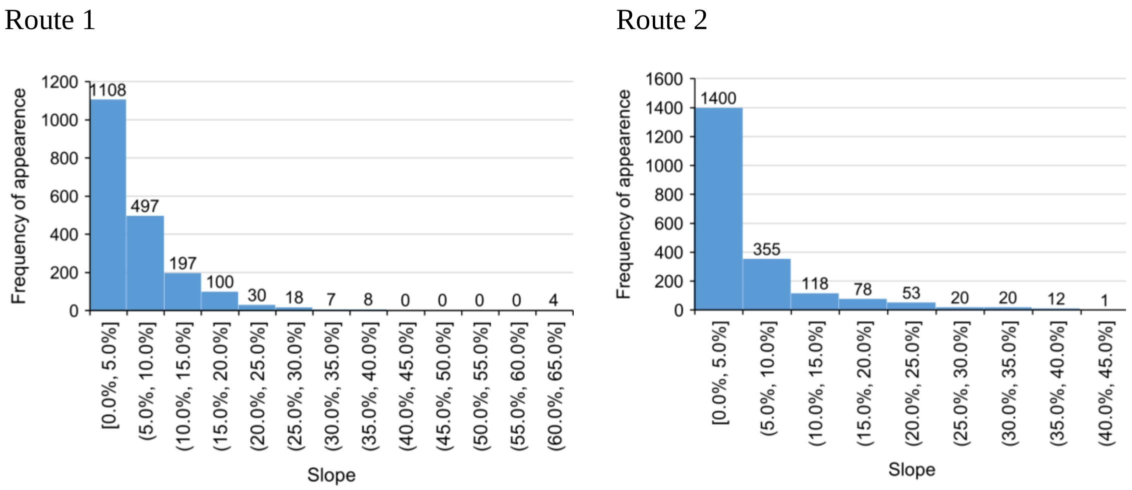


Fig. C1. Number of positive slope angles for both Routes 1 and 2.

# Appendix D

1. What is your opinion about the hydrogen bicycle driving behaviour?

   ☐Positive ☐Negative ☐Neutral

2. If positive/neutral, how much do you rate the driving experience (1 for acceptable and 10 for excellent)?

   ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10

3. If negative, what is the main reason?

   ☐Safety issues ☐Weight ☐Complex operation

   ☐Other (state):

4. Would you use the hydrogen bike for your daily transportation needs (e.g. going to work, super market)?

   ☐Yes ☐No

5. If “No”, what is the main reason for your answer?

   ☐Fuel cost ☐Low range ☐Long refuelling time

   ☐Other (state):

6. If “Yes”, up to what retail price of hydrogen fuel are you willing to pay for refuelling your vehicle?

   ☐1 DKK ☐5 DKK ☐10 DKK ☐50 DKK ☐Other (state):

7. For your daily transportation needs (range of the bike), what is the maximum distance that you are willing to travel to find a refuelling station?

   ☐ <1 km ☐1 km ☐2 km ☐Other (state):

# Appendix E

Table E1. Parameters used during the financial evaluation of the PhD research.

| Parameter | Symbol | Value | Unit | Source |
|---|---|---|---|---|
| Electrolysis system cost (for PEM incl. power electronics, BOP) | $IC_{el}$ | 1,200 (Alkaline), 3,130 (PEM) | €/kW | (Bertuccioli et al., 2014; Cortes and Green, 2019; Schmidt et al., 2017) |
| Cost of WT installation | $IC_{WT}$ | 1,477 | €/kW | (IRENA, 2018) |
| $H_2$ compressor cost | $IC_{comp}$ | 19,400 | €/kW | (Ulleberg and Hancke, 2020) |
| $H_2$ buffer tank cost per mass capacity | $IC_{bfr}$ | 374 | €/kg$H_2$ | (Wang et al., 2012) |
| 350 bar $H_2$ tank cost per mass capacity | $IC_{H2stor}$ | 477 | €/kg$H_2$ | (Law et al., 2013) |
| $H_2$ dispenser cost (per hose) | $IC_d$ | 22,500 | € | (Parks, 2014) |
| Control and safety system cost | $IC_{CS}$ | 255 | €/kg/day | (Melaina and Penev, 2013; Reddi et al., 2017) |
| MH refuelling system (connector and cooling systems)(1) | $IC_{MHsys}$ | 5,400 | € | (Popa et al., 2016) |
| Construction work parameter | $f_{cost,constr}$ | 0.15 | - | (Gim and Yoon, 2012) |
| Contingency parameter | $f_{cost, cont}$ | 0.08 | - | (Gim and Yoon, 2012) |
| Income tax factor | $\Phi$ | 0.22 (DK), 0.28 (GR)(2) | - | (European Commission, 2019c) |
| Daily operating hours | $h_{operat}$ | 13 | h | - |
| Annual labour cost | $PO$ | 57,394 (DK), 17,589 (GR) | € | (OECD, 2019b; Statistics Denmark, 2018b) |
| Electrolyser energy consumption | $E_{electr}$ | 56.3 | kWh/kg$H_2$ | (Perez and Casero, 2019) |
| Compressor energy consumption(3) | $E_{comp}$ | 2.45 (30 bar), 4.1 (100 bar), 4.25 (150 bar), 6.7 (200 bar) | kWh/kg$H_2$ | (Burheim, 2017; HOFER Hochdrucktechnik GmbH, 2010) |
| MH cooling system energy consumption | $E_{MH,cool}$ | 0.92 | kWh/kg$H_2$ | (Lototskyy et al., 2016b) |
| Electricity price(4) | $Rel$ | 0.084 (DK), 0.105 (GR) | €/kWh | (Eurostat, 2020c) |
| Annual maintenance cost parameter | $FC_{par}$ | 0.02 | - | (Katikaneni et al., 2014; Liu et al., 2016) |
| Electrolysis stack replacement | $FC_{el}$ | 0.30 $IC_{el}$ | € | (Weidner et al., 2018) |
| Annual O&M costs | $FC_{OM}$ | $FC_{par}\, IC_o + E_{cons} * 0.084^{(2)} + FC_{el}$ | € | (Katikaneni et al., 2014; Liu et al., 2016) |
| Delivered hydrogen cost | $FC_{H2}$ | 5.8 | €/kg$H_2$ | (Apostolou, 2020a; IEA, 2019c) |
| Annual insurance cost | $In$ | 0.01 $IC_o$ | € | (Katikaneni et al., 2014) |
| Land lease per sqm | $Rm$ | 2 | €/$m^2$ | (Lokaleportalen, 2020; Qadrdan and Shayegan, 2008) |
| Land lease (annual) | $Rn$ | $12 * footprint * Rm$ | € | - |

| Parameter | Symbol | Value | Unit | Source |
|---|---|---|---|---|
| Depreciation | $Ad_j$ | $0.1(IC_o - Ad_{j-1})$ | - | (Hulten et al., 1981) |
| Loan rate of interest | $i$ | 0.033 (DK), 0.035 (GR) | - | (Bank of Greece, 2020; National Bank - Statbank, 2020) |
| Weighted average cost of capital(5) | $r_c$ | 0.030 (DK), 0.117(GR) | - | (Steffen, 2020) |

[1] The MH refuelling system cost includes the assumed cost for the three quick coupling connectors (i.e. €1,000) and the cost of the cooling system (i.e. 800 €/$kW_{el}$).

[2] DK and GR stand for the values corresponding to Denmark and Greece, respectively.

[3] The energy consumption of the compressor is the sum of the energy required to compress hydrogen gas to 350 bar plus the energy consumed to get 1 $kgH_2$ from the compressor's outlet.

[4] The average electricity costs in 2019 for non-household consumers (20 MWh < $E_{cons}$ < 500 MWh).

[5] $r_c$ estimated for wind energy projects in Denmark, and solar PV and wind energy projects in Greece.

# Appendix F

Table F1. Physical characteristics of the participants.

| ID | Gender | Age (years) | Weight (kg) |
|---|---|---|---|
| Subject 1 | Male | 34 | 72 |
| Subject 2 | Female | 35 | 68 |
| Subject 3 | Male | 20 | 76 |
| Subject 4 | Male | 35 | 70 |
| Subject 5 | Male | 40 | 88 |
| Subject 6 | Male | 20 | 74 |
| Subject 7 | Male | 20 | 73 |
| Subject 8 | Male | 29 | 84 |
| Subject 9 | Male | 24 | 77 |
| Subject 10 | Female | 21 | 59 |
| Subject 11 | Male | 40 | 101 |
| Subject 12 | Female | 27 | 56 |
| Subject 13 | Female | 29 | 65 |
| Subject 14 | Male | 39 | 98 |
| Subject 15 | Male | 41 | 99 |
| Subject 16 | Female | 33 | 55 |

Table F2. Acquired data from the experimental phase.

| Participants | Route | Energy consumption (kWh) | $H_2$ consumed (g) | Refuelling time (h) | Range of the FCEB (km) | Average speed of the FCEB (km/h) |
|---|---|---|---|---|---|---|
| **Case (a)** | | | | | | |
| Subject 1 | 2 | 1.3 | 16.4 | 2.0 | 26.1 | 22.5 |
| Subject 2 | 1 | 1.1 | 15.3 | 1.8 | 25.4 | 18.1 |
| Subject 3 | 2 | 1.1 | 15.3 | 1.8 | 22.5 | 19.3 |
| Subject 4 | 2 | 1.3 | 16.5 | 1.9 | 25.8 | 21.2 |
| Subject 5 | 2 | 1.1 | 14.9 | 1.8 | 36.1 | 19.0 |
| Subject 6 | 1 | 1.0 | 13.2 | 1.6 | 36.9 | 23.4 |
| Subject 7 | 1 | 1.0 | 12.5 | 1.6 | 36.6 | 23.3 |
| Subject 8 | 1 | 0.9 | 13.2 | 1.6 | 37.0 | 19.7 |
| Subject 9 | 1 | 1.1 | 13.2 | 1.6 | 34.3 | 23.9 |
| Subject 10 | 2 | 1.3 | 15.9 | 1.9 | 31.7 | 21.6 |
| **Case (b)** | | | | | | |
| Subject 1 | 2 | 0.43 | 4.8 | 0.5 | 14.7 | 19.0 |
| Subject 2 | 1 | 0.39 | 4.9 | 0.5 | 17.9 | 21.8 |
| Subject 3 | 1 | 0.40 | 5.0 | 0.6 | 17.3 | 17.9 |
| Subject 4 | 2 | 0.41 | 4.8 | 0.6 | 13.0 | 21.8 |
| Subject 5 | 1 | 0.41 | 4.7 | 0.6 | 13.8 | 19.8 |
| Subject 6 | 2 | 0.41 | 4.8 | 0.5 | 17.4 | 18.8 |

Table F3. Statistical analysis for the energy consumption, hydrogen consumed to FCEB range ratios and refueling time during the experiments.

| | **Energy consumption to range ratio (kWh/km)** | **Refuelling time (h)** | **$H_2$ consumed to FCEB range ratio ($kgH_2$/km)** |
|---|---|---|---|
| | | **Case (a)** | |
| Mean | 0.038 | 1.760 | 0.0005 |
| Median | 0.038 | 1.800 | 0.0005 |
| Std. deviation | 0.001 | 0.151 | 0.0001 |
| Skewness | 0.073 | 0.127 | 0.2480 |
| Std. error of skewness | 0.687 | 0.687 | 0.6870 |
| | | **Case (b)** | |
| Mean | 0.026 | 0.550 | 0.0003 |
| Median | 0.026 | 0.550 | 0.0003 |
| Std. deviation | 0.004 | 0.055 | 0.0000 |
| Skewness | 0.061 | 0.000 | 0.4420 |
| Std. error of skewness | 0.845 | 0.845 | 0.8450 |

Table F4. Descriptive statistics of the participants' questionnaire answers.

| | **Column 1** | **Column 2** | **Column 3** | **Column 4** | **Column 5** |
|---|---|---|---|---|---|
| | FCEB behaviour | Driving experience | Use for daily needs | Refuelling cost willing to pay | Distance willing to travel to refuel |
| Mean | 1.38 | 7.88 | 1.25 | 3.63 | 3.19 |
| Median | 1.00 | 8.00 | 1.00 | 3.00 | 3.00 |
| Std. Deviation | 0.81 | 0.88 | 0.45 | 1.54 | 1.38 |
| Skewness | 1.77 | -0.39 | 1.28 | 0.72 | 0.14 |
| Std. Error of Skewness | 0.56 | 0.56 | 0.56 | 0.56 | 0.56 |
| Kurtosis | 1.28 | -0.28 | -0.44 | -0.97 | -1.51 |
| Std. Error of Kurtosis | 1.09 | 1.09 | 1.09 | 1.09 | 1.09 |

Table F5. Specifications of the FCES. Based on (Hwang, 2012; Tso et al., 2012).

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| PEM FC rated power | 1.9 | kW |
| Metal hydride tank capacity | 90 | $gH_2$ |
| Refuelling pressure | 10 | bar |
| Average fuel consumption (variable speed) | 1.9 | $gH_2$/km |

Table F6. Energy, fuel consumption, refuelling time and cost of commercialised vehicles for urban transportation. Based on (Bishop et al., 2011; Bosch GmbH, 2019; Braun and Rid, 2017; Eurostat, 2019d; Fishman and Cherry, 2015; Global Petrol Prices, 2019; Huang, 2018; IEA, 2012; Salmeron-Manzano and Manzano-Agugliaro, 2018).

| | **Average recharging[1] (Wh/km)** | **Average (regular charger) recharging time (SOC=100%) (h)** | **Average petrol/diesel consumption (L/km)** | **Average petrol/diesel refuelling time[2] (h)** | **Cost (€/km)** |
|---|---|---|---|---|---|
| Battery electric bicycle (BEB) | 20 | 5.0 | - | - | 0.006 |
| Battery electric scooter (BES) | 100 | 5.0 | - | - | 0.031 |
| Battery electric vehicle (BEV) | 222 | 6.5 | - | - | 0.068 |
| Petrol scooter | - | - | 0.03 | 0.02 | 0.046 |
| Small petrol car | - | - | 0.05 | 0.03 | 0.077 |
| Small diesel car | - | - | 0.04 | 0.03 | 0.054 |

[1] Taking into account the vehicles' average energy consumption (Wh/km) and an average charger's efficiency of 90% (Kong, 2018).

[2] Based on the single dispenser max. flow rate equalling to 40 L/min and an average tank volume of 45 L (cars) and 5.5 L (scooters) (Direct Bikes, 2019; Tatsuno Europe, 2019; Yamada et al., 2018).

# Appendix G

Table G1. Physical characteristics of the participants and FCEB range correlation statistical analysis for case (a).

| | | | Gender | Range | Age | Weight |
|---|---|---|---|---|---|---|
| Spearman's rho | Gender | Correlation coefficient | 1.000 | -.348 | .133 | -.696* |
| | | Sig. (2-tailed) | . | .324 | .715 | .025 |
| | | N | 10 | 10 | 10 | 10 |
| | Range | Correlation coefficient | -.348 | 1.000 | -.197 | .491 |
| | | Sig. (2-tailed) | .324 | . | .586 | .150 |
| | | N | 10 | 10 | 10 | 10 |
| | Age | Correlation coefficient | .133 | -.197 | 1.000 | .025 |
| | | Sig. (2-tailed) | .715 | .586 | . | .946 |
| | | N | 10 | 10 | 10 | 10 |
| | Weight | Correlation coefficient | -.696* | .491 | .025 | 1.000 |
| | | Sig. (2-tailed) | .025 | .150 | .946 | . |
| | | N | 10 | 10 | 10 | 10 |

*Correlation is significant at the 0.05 level (2-tailed).

Table G2. Physical characteristics of the participants and FCEB range correlation statistical analysis for case (b).

| | | | Age | Weight | Gender | Range |
|---|---|---|---|---|---|---|
| Spearman's rho | Age | Correlation coefficient | 1.000 | .771 | -.878* | -.771 |
| | | Sig. (2-tailed) | . | .072 | .021 | .072 |
| | | N | 6 | 6 | 6 | 6 |
| | Weight | Correlation coefficient | .771 | 1.000 | -.878* | -.714 |
| | | Sig. (2-tailed) | .072 | . | .021 | .111 |
| | | N | 6 | 6 | 6 | 6 |
| | Gender | Correlation coefficient | -.878* | -.878* | 1.000 | .878* |
| | | Sig. (2-tailed) | .021 | .021 | . | .021 |
| | | N | 6 | 6 | 6 | 6 |
| | Range | Correlation coefficient | -.771 | -.714 | .878* | 1.000 |
| | | Sig. (2-tailed) | .072 | .111 | .021 | . |
| | | N | 6 | 6 | 6 | 6 |

*Correlation is significant at the 0.05 level (2-tailed).

# Appendix H


Fig. H1. FCEB route during the experiment.

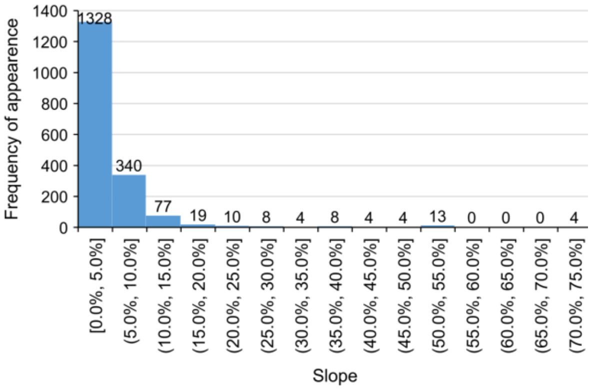



Fig. H2. Number of positive slope angles during the followed route.

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES AARHUS UNIVERSITY

# Co-Author Statements

## Article 3.1

### Declaration of co-authorship*

Full name of the PhD student: Dimitrios Apostolou

This declaration concerns the following article/manuscript:

| | |
|---|---|
| Title: | A Literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects |
| Authors: | Dimitrios Apostolou, George Xydis |

The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference: D. Apostolou, G. Xydis (2019). A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. Renewable & Sustainable Energy Reviews, 113, 109292, https://doi.org/10.1016/ j.rser.2019.109292.

If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No ☒ Yes ☐ If yes, give details:

The PhD student has contributed to the elements of this article/manuscript as follows:

- A. Has essentially done all the work
- B. Major contribution
- C. Equal contribution
- D. Minor contribution
- E. Not relevant

| Element | Extent (A-E) |
|---|---|
| 1. Formulation/identification of the scientific problem | C |
| 2. Planning of the experiments/methodology design and development | A |
| 3. Involvement in the experimental work/clinical studies/data collection | A |
| 4. Interpretation of the results | A |
| 5. Writing of the first draft of the manuscript | A |
| 6. Finalization of the manuscript and submission | C |

**Signatures of the co-authors**

| Date | Name | Signature |
|---|---|---|
| 10/12/2020 | George Xydis | |

In case of further co-authors please attach appendix

Date: 10/12/2020

Signature of the PhD student

**Article 3.2**

## Declaration of co-authorship*

Full name of the PhD student: Dimitrios Apostolou

This declaration concerns the following article/manuscript:

| | |
|---|---|
| Title: | Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark |
| Authors: | Dimitrios Apostolou, Sissel Welcher |

The article/manuscript is: Published ☐ Accepted ☒ Submitted ☐ In preparation ☐

If published, state full reference:

If accepted or submitted, state journal: International Journal of Hydrogen Energy

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No ☒ Yes ☐ If yes, give details:

The PhD student has contributed to the elements of this article/manuscript as follows:

A. Has essentially done all the work
B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

| Element | Extent (A-E) |
|---|---|
| 1. Formulation/identification of the scientific problem | A |
| 2. Planning of the experiments/methodology design and development | B |
| 3. Involvement in the experimental work/clinical studies/data collection | B |
| 4. Interpretation of the results | A |
| 5. Writing of the first draft of the manuscript | D |
| 6. Finalization of the manuscript and submission | A |

**Signatures of the co-authors**

| Date | Name | Signature |
|---|---|---|
| 05/12-20 | Sissel Welcher | |

In case of further co-authors please attach appendix

Date: 05/12/2020

Signature of the PhD student

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES AARHUS UNIVERSITY

**Article 4.1**

## Declaration of co-authorship*

Full name of the PhD student: Dimitrios Apostolou

This declaration concerns the following article/manuscript:

| | |
|---|---|
| Title: | The past, present and potential of hydrogen as a multifunctional storage application for wind power |
| Authors: | Dimitrios Apostolou, Peter Enevoldsen |

The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference: D. Apostolou, P. Enevoldsen (2019). The past, present and potential of hydrogen as a multifunctional storage application for wind power. Renewable and Sustainable Energy Reviews, 112, pp. 917-929, https://doi.org/10.1016/ j.rser.2019.06.049..

If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No ☒ Yes ☐ If yes, give details:

The PhD student has contributed to the elements of this article/manuscript as follows:

A. Has essentially done all the work
B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

| Element | Extent (A-E) |
|---|---|
| 1. Formulation/identification of the scientific problem | C |
| 2. Planning of the experiments/methodology design and development | B |
| 3. Involvement in the experimental work/clinical studies/data collection | B |
| 4. Interpretation of the results | B |
| 5. Writing of the first draft of the manuscript | C |
| 6. Finalization of the manuscript and submission | A |

**Signatures of the co-authors**

| Date | Name | Signature |
|---|---|---|
| 07/12/2020 | Peter Enevoldsen | Peter Enevoldsen Digitally signed by Peter Enevoldsen DN: cn=Peter Enevoldsen, c=DK, o=Aarhus University, ou=AU, email=peterenevoldsen@btech.au.dk Date: 2020.12.07 10:37:13 +01'00' |

In case of further co-authors please attach appendix

Date: 10/12/2020

________________________________________
Signature of the PhD student

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

**Article 5.1**

## Declaration of co-authorship*

Full name of the PhD student: Dimitrios Apostolou

This declaration concerns the following article/manuscript:

| | |
|---|---|
| Title: | Supporting green urban mobility – The case of a small scale autonomous $H_2$ refuelling station |
| Authors: | Dimitrios Apostolou, Peter Enevoldsen, George Xydis |

The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference: D. Apostolou, P. Enevoldsen, G. Xydis (2019). Supporting green urban mobility – The case of a small scale autonomous H2 refuelling station. International Journal of Hydrogen Energy, 44(20), pp. 9675-9689, https://doi.org/10.1016/j.ijhydene.2018.11.197.

If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No ☒ Yes ☐ If yes, give details:

The PhD student has contributed to the elements of this article/manuscript as follows:

A. Has essentially done all the work
B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

| Element | Extent (A-E) |
|---|---|
| 1. Formulation/identification of the scientific problem | A |
| 2. Planning of the experiments/methodology design and development | A |
| 3. Involvement in the experimental work/clinical studies/data collection | C |
| 4. Interpretation of the results | A |
| 5. Writing of the first draft of the manuscript | A |
| 6. Finalization of the manuscript and submission | B |

**Signatures of the co-authors**

| Date | Name | Signature |
|---|---|---|
| 07/12/2020 | Peter Enevoldsen | Peter Enevoldsen Digitally signed by Peter Enevoldsen DN: cn=Peter Enevoldsen, c=DK, o=Aarhus University, ou=AU, email=peterenevoldsen@btech.au.dk Date: 2020.12.07 10:38:08 +01'00' |
| 08/12/2020 | George Xydis | |

In case of further co-authors please attach appendix

Date: 09/12/2020

_______________________________________________
Signature of the PhD student

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES AARHUS UNIVERSITY

**Article 5.3**

## Declaration of co-authorship*

Full name of the PhD student: Dimitrios Apostolou

This declaration concerns the following article/manuscript:

| | |
|---|---|
| Title: | Integration of a light mobility urban scale hydrogen refuelling station for cycling purposes in the transportation market |
| Authors: | Dimitrios Apostolou, Pedro Casero, Vanesa Gil, George Xydis |

The article/manuscript is: Published ☐ Accepted ☒ Submitted ☐ In preparation ☐

If published, state full reference:

If accepted or submitted, state journal: International Journal of Hydrogen Energy

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No ☒ Yes ☐ If yes, give details:

The PhD student has contributed to the elements of this article/manuscript as follows:

A. Has essentially done all the work
B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

| Element | Extent (A-E) |
|---|---|
| 1. Formulation/identification of the scientific problem | A |
| 2. Planning of the experiments/methodology design and development | B |
| 3. Involvement in the experimental work/clinical studies/data collection | B |
| 4. Interpretation of the results | A |
| 5. Writing of the first draft of the manuscript | A |
| 6. Finalization of the manuscript and submission | B |

**Signatures of the co-authors**

| Date | Name | Signature |
|---|---|---|
| 10/12/2020 | Pedro Casero | |
| 11/12/2020 | Vanesa Gil | GIL HERNANDEZ VANESA - 29130689Q Firmado digitalmente por GIL HERNANDEZ VANESA - 29130689Q Fecha: 2020.12.10 22:30:42 +01'00' |
| 09/12/2020 | George Xydis | |

In case of further co-authors please attach appendix

Date: 12/12/2020

________________________________________

Signature of the PhD student