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Investigating the feasibility of Electric Vehicles and Vehicle-to-Grid in the Nordic region: a path for adoption.

PhD dissertation

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Executive Summary

Electric vehicles (EVs) have become the most prominent technology for the prospect of decarbonising passenger transportation, when coupled with a low carbon energy system. As a result, the focus on electric vehicle technology, and the sociotechnical systems around it, has increased in the last decade across scientific, industrial and political circles. Consequently, the global push for this electric powered technology is transforming well established systems such as the automotive vehicle supply and selling chains. At the same time, deriving from EVs, vehicle-to-grid (V2G) technology is the technical capability of EVs that allows for a dual flow of communication and power, in other words it enables bi-directionality. Through this ability, V2G-capable EVs open a range of new opportunities and provide electric grid services, along with other new potential applications. Ultimately, V2G allows to maximise the value and capability of EVs by achieving cross-system integration between the transport and energy systems, but also with other collateral systems such as the building and residential sector.

Despite the great promise and progress of these technologies, the transition towards electrification has not made equal progress globally, facing several impediments for social diffusion, even across the apparent natural fits for the technology; such as national markets with high levels of renewable energy integrated into the power system. The challenges for these technologies have been well documented particularly from a technical perspective, including elements such as battery capacity, reliability and performance, driving range and other techno-economic such as their capital cost or life cycle costs in comparison with other technologies. However, if EVs are set to be used as tools for decarbonisation it is necessary to both understand their impact across different system levels, as well as investigate and identify paths to foster their social diffusion, considering that the speed of technological advances creates a continuous evolution of the EV market. Thus, EVs have moved from pilot or experimental cars to starting to replace the traditional petrol and diesel vehicles on a large scale in consumer markets.

To explore the prospect of EV and V2G diffusion, this PhD dissertation proposes three research questions. These aim to investigate electric mobility across three distinct levels: the consumer and retail level (Research Question 1), the meso-level (Research Question 2) and the system wide implications (Research Question 3). The research questions are:

- Research Question 1: How are electric vehicles diffused in the retail and consumer level?
- Research Question 2: What are the structural barriers and benefits of electric vehicles and vehicle to grid?
- Research Question 3: What is the system impact of electric vehicles and vehicle to grid?

In the process of answering these questions, over 23 scientific articles have been published and submitted, with six research articles being presented in this doctoral dissertation. Research Question 1 comprises of two articles: 1) *Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale* and 2) *Who will buy EVs after early adopters? Using machine learning to identify EV mainstream buyers and their characteristics*. Research Question 2 includes two journal articles: 3) *Understanding the Socio-technical Nexus of Electric Vehicle (EV) Barriers: A qualitative discussion of Range, Price, Charging and Knowledge* and 4) *Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)*. The Research Question 3 includes two following journal articles: 5) *The market case for electric mobility: Investigating electric vehicle business models for mass adoption* and 6) *Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark.*

The research followed a mixed method approach to undercover the insights from socio-technical systems, in this case the one consisting of electric mobility that combines the electricity and transport structures. In doing so, the project navigated through an interdisciplinary scope that includes elements from business, economic, engineering, political and environmental science; resulting in both holistic and tangible outputs which are relevant to stakeholders in academia, industry, consumer markets, and policy decision-making. Additionally, the international scope of the project, focusing in the five countries of Denmark, Finland, Iceland, Norway and Sweden, allows for the results and insights to be extrapolated not only to other specific geographies but also other technological contexts; for example, in the introduction of other technologies such as automated vehicles, storage solutions and renewable-based technologies (e.g. solar kitchens). Ultimately, this PhD dissertation aims to explore a roadmap for EV and V2G adoption, within the Nordic region but also internationally, and serve as a map for technology innovation and diffusion.

The first journal article (*Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale)* looked to answer Research Question 1 (*How are electric vehicles diffused in the retail and consumer level?*) by investigating the automotive retail space, focusing specifically on car dealerships. The study explores the strategies, methods and approaches of car dealerships in promoting (or not) electric vehicles to prospective automotive consumers. Therefore, it analyses potential bottlenecks across the automotive supply chain for the diffusion of EVs into society. The study uses a multi-method approach based on 126 shopping experiences at 82 car dealerships across 15 cities in the five Nordic countries between 2016 and 2017. To ensure validity, the primary method is triangulated with 30 expert interviews of transport and energy related organisations across the Nordic region.

The results show that car dealerships pose a significant barrier in the likeliness of consumers purchasing EVs at the point of sale. This finding is a result of current market conditions that favour petrol and diesel vehicles where, due to a lack of pre-existing consumer knowledge on EVs, car dealerships may strongly influence purchasing behaviours away from these electric technologies. In doing so, the study find that dealers were dismissive of EVs, misinformed shoppers on vehicle specifications, excluded EVs in sales conversations and strongly oriented customers towards petrol and diesel vehicle options. The findings ultimately show that government and industry signalling affect sales strategies and purchasing of electric vehicles; where outside of Norway, petrol and diesel vehicles still receive more favourable retail market conditions in terms of vehicle taxation, sales strategy and vehicle promotion, which detriments EV uptake. Through this article, this dissertation presents the retail space as both a challenge and a prospect to foster EV diffusion.

The second article (*Who will buy EVs after early adopters? Using machine learning to identify electric vehicle mainstream buyers and their characteristics*) also looked to answer Research Question 1 (*How are electric vehicles diffused in the retail and consumer level?*) by focusing in exploring the consumer level of the automotive market, in particular, the prospective mainstream market of EVs. Considering that current EV penetration remains in nascent stages, if electric vehicles are expected to greatly decarbonise passenger transportation, they must reach mainstream consumer segments and move beyond current early adopters and pioneers. Therefore, this study investigates the underlying causes of EV interest, to determine the potential next wave of EV buyers and highlights strategies to reach these segments.

For this purpose, the study draws data from an online survey (n = 5067) across the five Nordic countries, and through the use of a machine learning model and a k-means method, it finds six consumer segments around prospective EV adoption. In particular, the results show that three consumer clusters that account for 68% of the population represent the near-term mainstream EV market. It notes that that price is a main determinant for EV adoption, and in this case, for reaching these mainstream consumers, while also suggesting that effective EV promotion strategy should focus on the technological attributes of vehicles, as opposed to their environmental characteristics. Finally, the study corroborates and stresses the importance of an equally competitive market place for EVs, and for industry and decision-makers to develop strategies and policy that considers the characterises and interests of mainstream EV customers. Hence, in introducing this article, the dissertation highlights the need to explore the entirety of the potential EV consumer market, showcasing prospective strategies to promote EV diffusion.

The third article (*Understanding the Socio-technical Nexus of Electric Vehicle (EV) Barriers: A qualitative discussion of Range, Price, Charging and Knowledge)* investigates Research Question 2 (What are the structural barriers and benefits of electric vehicles?) by exploring the structural barriers for electric vehicle adoption. The aim is to understand the underlaying barriers for diffusing electric vehicles into society by exploring the potential comprehensive array of challenges these electric technologies face. The article uses as primary method an original sample of 227 semi-structured interviews with transportation and electricity experts from 201 institutions across seventeen cities in the Nordic region.

The qualitative results firstly show that frequently discussed barriers like range, price and charging infrastructure continue to be perceived as the main challenge for EV adoption, despite the significant and continuous technological advancements across the last few years. Notably, however, the study also finds that while these top barriers are considered as the main impediments for EV, they are also the ones that are expected to be organically addressed as the technology and the markets continues to mature. Moreover, through a cluster analysis, the results also show that there is a high degree of interconnection between the identified barriers, and a variety of technical barriers which are connected primarily to consumer knowledge and experience. Therefore, this article reinforces both the importance of the social elements that go in hand with the technology and its diffusion, and also that strategies for deployment should consider such interconnectedness; as policy that influences consumer knowledge can address other structural barriers such as range and charging infrastructure.

The fourth article (*Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)*) looks into Research Question 2 (What are the structural barriers and benefits of electric vehicles?) to explore an entire array of benefits that EVs and V2G can offer to society. Despite the apparent cost-saving benefits of EVs, the technology has faced several barriers for penetrations and thus, this article highlights the areas of potential value to outweigh its challenges. This paper uses the same methodology as the second article analysing the set of 227 semi-structured interviews with transportation and electricity experts from over 200 institutions across the Nordic region.

The findings elaborate on a comprehensive range of benefits for both EVs and V2G, as the interviewed experts suggested 29 EV and 25 V2G distinct categories of benefits. Within these benefits, the article introduced the frequently discussed benefits of these technologies, such as economic savings, emission-reduction potential, and renewable energy integration. Notably, several other novel benefits were identified including the potential for noise reduction and better technical vehicle performance, which are the second and third most discussed benefits. At the same time, V2G benefits included themes likes vehicle-to-home and solar PV integration, along with other novel benefits such as vehicle-to-telescope and emergency power backup provision. Through this article, this dissertation brings forward the potential value of EVs and V2G in the path for their social diffusion.

The fifth article (*The market case for electric mobility: Investigating electric vehicle business models for mass adoption*) provides answers to the Research Question 3 (What is the system impact of electric vehicles and vehicle-to-grid?) looking into the current and future business implications of EVs; as the technology progresses from a niche to early and mass markets. The methodology applied to this paper follows the previous two articles above by replying on a robust sample of 227 semi-structured interviews, conducted by the authors, with transportation and electricity experts from 201 institutions across seventeen cities in Denmark, Finland, Iceland, Norway, and Sweden.

The article finds that EVs currently face an unfavourable business case, along with the national market conditions, have led to the legacy of the internal combustion car industries. As a result, electric vehicles currently have an unsuitable business model and supply chain that compromises the production and promotion of this vehicle technology. In addition, the paper finds that for a system-wide diffusion, in other words when EVs become a mainstream vehicle option, EVs will transform the traditional automotive selling chain, directly affecting selling methods, maintenance revenue streams and refuelling (recharging) structures. Therefore, it explores the need to adopt new system configurations to maximise the benefits of EVs, and that are suitable for their diffusion. This article thus introduces to this dissertation the system effects of electric vehicle diffusion from a business and supply chain perspective.

The sixth and final article (*Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark)* introduced in this PhD dissertation looks into answering Research Question 3 (What is the system impact of electric vehicles and vehicle to grid?), by exploring the social costs and benefits of different system configurations of EVs, including and excluding the use of V2G. For this purpose, and in order to explore the benefits and costs of different electric vehicle pathways, the article creates four different scenarios, based on the current and future Danish electricity grid. The scenarios include the combination of different levels of EV penetration in the national fleet, as well as communication ability – referring to smart charging or full bi-directionality (V2G) – and then coupled with different levels of future renewable energy implementation.

The paper then calculates the potential societal costs for all scenarios, including externalities of carbon and health in order to find the least-cost mix of electric vehicle penetration in society. As a result, the article finds that the most cost-effective penetration of electric vehicles in the immediate future is 27%, increasing to 75% by 2030, which would account to a reduction of $34 billion in societal costs in 2030, a decrease of 30% compared to a business as usual scenario. However, the today's unfavourable market conditions for electric vehicles such as capital cost differences, or lack of willingness to pay, coupled with consumer implied discount rates, represent substantial barriers for electric vehicle penetration in Denmark. This article, thus explores the system impacts of the introduction of EVs and V2G, highlighting their potential within social-wide diffusion.

In sum, this PhD dissertation presents these six articles to answer three central research questions through the use of a multi-method approach that includes both quantitative and qualitative methodologies. In doing so, it follows the multidisciplinary and holistic approach to understand the socio-technical elements that surround the diffusion of EVs and V2G into society. The dissertation then elaborates and concludes with a prospective roadmap for electric mobility adoption where it proposes specific measures create a space in which electric vehicles can be produced, promoted, operated and diffused onto wider society; ultimately, enabling and maximising its decarbonisation potential.

Danish summary

Kombineret med et lav-CO_2-energisystem er elektriske køretøjer blevet den mest fremtrædende teknologi til at nedbringe mængden af CO_2 fra biltransport. De sidste ti år er der som følge heraf kommet mere fokus på elbilteknologien i politiske, videnskabelige og forretningsmæssige kredse, hvor det globale pres for at integrere elektrisk teknologi er ved at ændre veletablerede systemer, herunder bilforsynings- og salgskæder. Samtidig giver den såkaldte 'vehicle to grid'-teknologi (V2G) eller på dansk 'bil-til-net' også mulighed for, at elbiler ikke blot lader op fra elnettet, men også kan levere energi tilbage. Dermed åbner V2G-teknologien op for nye muligheder og services til elnettet sammen med en række potentielle applikationer. V2G-teknologien kan dermed bidrage til at forbedre elektriske køretøjers værdi og robusthed ved at opnå systemintegration ikke kun på tværs af transport- og energisystemerne, men også med andre sikkerhedssystemer inden for f.eks. bygge- og boligsektoren.

Selvom der sker store fremskridt inden for disse teknologier, er det også meget forskelligt, hvor langt man er nået i overgangen til elektrificering globalt set – selv der, hvor teknologien helt naturligt kunne være implementeret, f.eks. steder med et højt niveau af vedvarende energi integreret i elsystemet. De teknologiske udfordringer har været veldokumenteret specielt på den tekniske side, herunder batterikapacitet, pålidelighed og ydeevne, rækkevidde og andre tekno-økonomiske elementer, såsom totalomkostninger eller livscyklusomkostninger, sammenlignet med andre teknologier. Men hvis elbiler skal bruges til at reducere CO_2-udledningen, er det nødvendigt at forstå deres indflydelse på tværs af forskellige systemniveauer samt undersøge og identificere tiltag, der kan fremskynde deres udbredelse. Dette sammenholdt med, at de teknologiske fremskridt ligeledes er med til at skabe en løbende udvikling i elbilmarkedet; i dag begynder forbrugerne at erstatte almindelige benzin- og dieselbiler med eldrevne køretøjer, der førhen kun blev brugt som demo- eller testbiler.

For at se på mulighederne for udbredelse af elektriske køretøjer og V2G-teknologien undersøger denne ph.d.-afhandling tre forskningsspørgsmål, der fokuserer på elektrisk mobilitet på tværs af tre forskellige niveauer: Forbruger- og detailniveauet (forskningsspørgsmål 1), meso-niveauet (forskningsspørgsmål 2) samt i forhold til systemmæssige implikationer (forskningsspørgsmål 3).

Forskningsspørgsmålene er:

- Forskningsspørgsmål 1: Hvordan udbredes antallet af elbiler på detail- og forbrugerniveau?
- Forskningsspørgsmål 2: Hvilke strukturelle barrierer og fordele er der ved elektriske køretøjer og V2G-teknologien?

- Forskningsspørgsmål 3: Hvad er systemets indvirkning på elektriske køretøjer og V2G-teknologien?

Til besvarelse af ovenstående spørgsmål er mere en 23 videnskabelige artikler blevet publiceret, hvoraf 6 af artiklerne er præsenteret i denne afhandling. Forskningsspørgsmål 1 består af to artikler: 1) *Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale* og 2) *Who will buy EVs after early adopters? Using machine learning to identify EV mainstream buyers and their characteristics*. Forskningsspørgsmål 2 omfatter to tidsskriftartikler: 3) *Understanding the socio-technical nexus of electric vehicle (EV) barriers: A qualitative discussion of range, price, charging and knowledge* og 4) *Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)*. Forskningsspørgsmål 3 består af følgende to tidsskriftartikler: 5) *The market case for electric mobility: Investigating electric vehicle business models for mass adoption* og 6) *Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark.*

Denne ph.d.-afhandling har anvendt en 'mixed methods'-tilgang til at give en forståelse for sociotekniske systemer – i dette tilfælde systemer, der består af elektrisk mobilitet – der kombinerer el- og transportstrukturer. Tilgangen har altså været tværfaglig med fokus på både økonomiske, teknikske, politiske og miljøvidenskabelige områder, hvilket har resulteret i holistiske og håndgribelige resultater, der er relevante for forskningsverden, industrien, forbrugerne og beslutningstagerne. Desuden giver afhandlingens internationale omfang, der inkluderer Danmark, Finland, Island, Norge og Sverige, mulighed for at ekstrapolere resultaterne ikke kun til andre specifikke geografiske områder, men også i andre teknologiske sammenhænge, f.eks. til at implementere andre teknologier såsom automatiserede køretøjer, lagringsløsninger og teknologier baseret på vedvarende energi (f.eks. solcelleanlæg). Sidst men ikke mindst undersøger denne ph.d.-afhandling muligheden for et 'roadmap' over elektriske køretøjer og V2G i den nordiske region og globalt, som skal illustrere den teknologiske innovation og udbredelse.

Den første tidsskriftartikel (*Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale*) ser på det første forskningsspørgsmål (*Hvordan udbredes antallet af elbiler på detail- og forbrugerniveau?*) ved at undersøge automobilområdet med særligt fokus på bilforhandlere. Artiklen undersøger bilforhandleres strategier, metoder og tilgange til at markedsføre (eller mangel på samme) eldrevne køretøjer over for potentielle bilkøbere. Derfor analyserer artiklen potentielle flaskehalse på tværs af bilforsyningskæden til udbredelse af elektriske køretøjer i samfundet. Undersøgelsen anvender en 'mixed-methods'-tilgang baseret på 126 købsoplevelser hos 82 bilforhandlere i 15 byer i de 5 nordiske lande mellem 2016 og 2017. For at sikre validitet i resultaterne er den primære metode trianguleret med 30 ekspertinterviews i transport- og energirelaterede organisationer på tværs af den nordiske region.

Resultaterne viser, at bilforhandlere udgør en betydelig barriere for sandsynligheden for køb af elbiler på salgsstedet. Denne konklusion er imidlertid et resultat af de nuværende markedsforhold, der favoriserer benzin- og dieselkøretøjer, hvor bilforhandlere grundet bilkøbernes manglende tekniske kendskab til elektriske køretøjer i høj grad kan påvirke købsbeslutningen i retning væk fra elbiler. Undersøgelsen viser, at bilforhandlere er afvisende over for elbiler, misinformerer kunderne omkring køretøjsspecifikationer, ikke nævner elbiler i en købssituation og favoriserer benzin- og dieselkøretøjer.

Resultaterne viser desuden, at regerings- og industriudmeldinger påvirker salgsstrategier og salg af elbiler; bortset fra Norge har benzin- og dieselkøretøjer stadig bedre markedsforhold i form af lavere afgifter, flere salgsparametre og bedre markedsføring, hvilket er med til at bremse udbredelsen af elbiler. Som en del af ph.d.-afhandlingen er formålet med denne artikel at se på detailhandlen med henblik på at fremme udbredelsen af elektriske køretøjer.

Den anden artikel (*Who will buy EVs after early adopters? Using machine learning to identify electric vehicle mainstream buyers and their characteristics*) har ligeledes til formål at svare på forskningsspørgsmål 1 (*Hvordan udbredes antallet af elbiler på detail- og forbrugerniveau?*). Her er fokus på antallet af forbrugere på bilmarkedet og især det fremtidige marked for salg af elbiler. Artiklen beskriver, at udbredelsen af elbiler i dag stadig kun er spirende, hvor de nuværende elbilejere kan karakteriseres som 'early adopters' eller pionerer, og hvis elbiler forventes at reducere CO_2-udledningen for personbiler væsentligt, skal de nå ud til almindelige forbrugersegmenter. Artiklen undersøger derfor de underliggende årsager til interessen for elbiler med henblik på at identificere den næste bølge af elbilkøbere samt belyse strategier til at målrette indsatsen mod disse segmenter.

Til dette formål trækker undersøgelsen på data fra en onlineundersøgelse (n = 5067) på tværs af de fem nordiske lande, og ved brug af en 'machine learning'-model baseret på k-means-metoden finder den seks forbrugersegmenter, hvor der er potentiale for, at elektriske køretøjer kan vinde indpas. Resultaterne viser, at især tre forbrugerklynger, der tegner sig for 68% af befolkningen, repræsenterer segmenter, hvor elbiler på mellemkort sigt kan erstatte konventionelle biler. Det er især prisen på elbiler, der er en afgørende faktor for udbredelsen, og derudover skal en målrettet markedsføringsindsats fokusere på elbilens teknologi frem for dens miljømæssige fordele. Sidst men ikke mindst bekræfter og understreger undersøgelsen vigtigheden af et mere lige konkurrencepræget marked for elbiler, og at industrien samt beslutningstagere udvikler strategier og vedtager love, der tager højde for den almindelige forbrugers karakteristika og interesser, når det kommer til elbiler. Med denne artikel introducerer ph.d.-afhandlingen derfor behovet for at undersøge det potentielle forbrugermarked for elbiler, der skal belyse potentielle strategier til at fremme udbredelsen af elektriske køretøjer.

Den tredje artikel (*Understanding the socio-technical nexus of electric vehicle (EV) barriers: A qualitative discussion of range, price, charging and knowledge)* søger at svare på forskningsspørgsmål 2 (*Hvilke strukturelle barrierer og fordele er der ved elektriske køretøjer og V2G-teknologien?*). Her undersøges de strukturelle barrierer for udbredelsen af elektriske køretøjer med henblik på at identificere de underliggende udfordringer, der hindrer udbredelsen af elektriske køretøjer, herunder de udfordringer, som de elektroniske teknologier står over for. Til undersøgelsen er de 227 semistrukturerede interviews med transport- og el-eksperter fra 201 institutioner i 17 nordiske byer blevet anvendt.

De kvalitative resultater viser først og fremmest, at ofte diskuterede barrierer som rækkevidde, pris og infrastruktur til opladning fortsat opfattes som de største udfordringer for udbredelsen af elbiler på trods af de betydelige og fortsatte teknologiske fremskridt, der har været de sidste par år. Undersøgelsen konkluderer imidlertid også, at mens disse primære udfordringer anses som de største i forbindelse med udbredelsen af elektriske køretøjer, så forventes de også at komme mere i fokus, efterhånden som teknologien og markederne modnes. På baggrund af en klyngeanalyse viser resultaterne også, at der er en større sammenhæng mellem de identificerede barrierer, og at tekniske barrierer har en tendens til at være forbundet med forbrugernes viden og erfaring. Ph.d.-afhandlingen understreger dermed ikke kun betydningen af de sociale elementer, der går hånd i hånd med teknologien og dens udbredelse, men også, at de strategier, der skal anvendes til implementeringen, bør rumme en sammenhængskraft, da lovgivningen, der påvirker forbrugernes viden, kan adressere andre strukturelle barrierer som f.eks. rækkevidde og infrastrukturen til opladning.

Den fjerde artikel (*Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)*) ser ligeledes på forskningsspørgsmål 2 (*Hvilke strukturelle barrierer og fordele er der ved elektriske køretøjer og V2G-teknologien?*) ved netop at undersøge alle fordelene ved elektriske køretøjer og V2G. For trods mange økonomiske fordele har teknologien haft svært ved at vinde indpas, og derfor belyser denne artikel de områder, der kan bidrage til at håndtere udfordringerne. Artiklen bruger samme metode som den tredje artikel (*Understanding the socio-technical nexus of electric vehicle (EV) barriers: A qualitative discussion of range, price, charging and knowledge*), der analyserer 227 semistrukturerede interviews med transport- og el-eksperter fra mere end 200 institutioner i de nordiske lande.

Resultaterne viser en lang række fordele ved både elektriske køretøjer og V2G-teknologien; de interviewede eksperter angav 29 forskellige fordele ved elektriske køretøjer og 25 for V2G-teknologien. De mest almindelige fordele ved teknologierne er blevet beskrevet, herunder de åbenlyse økonomiske besparelser, potentialet for CO_2-reducering samt integration af vedvarende energi. Flere andre nye fordele er ligeledes blevet identificeret, herunder potentialet for støjreduktion samt muligheden for bedre tekniske køreegenskaber (den anden og tredje mest omtalte fordel). Andre V2G-fordele omfatter 'bil-til-hjem'-funktioner og solcelleintegration sammen med andre nye fordele som f.eks. 'bil-til-teleskop' og nødkraftforsyning. Resultaterne fra denne artikel viser den potentielle værdi i udbredelsen af elektriske køretøjer og V2G-teknologien.

Den femte artikel (*The market case for electric mobility: Investigating electric vehicle business models for mass adoption*) giver svar på forskningsspørgsmål 3 (*Hvad er systemets indvirkning på elektriske køretøjer og V2G-teknologien?*), hvor der ses på de strukturelle nuværende og fremtidige forretningsmæssige konsekvenser for elbiler, som teknologien vinder mere og mere indpas. Metoden, der anvendes i artiklen, er den samme som i den tredje og fjerde artikel (ovenfor), nemlig de 227 semistrukturerede interviews med transport- og el-eksperter fra 201 institutioner i 17 nordiske byer i Danmark, Finland, Island, Norge og Sverige.

Artiklen konkluderer, at elektriske køretøjer p.t. ikke har de bedste betingelser grundet forbrændingsmotorens lange historie kombineret med nationale markedsforhold. Der findes altså p.t. ikke en egnet forretningsmodel og forsyningskæde til elbiler, som kan bruges til udviklingen og udbredelsen af denne teknologi. Derudover beskriver artiklen, at når elbiler bliver et almindeligt anvendt køretøj, vil den traditionelle bilforsyningskæde blive ændret betydeligt, hvad angår salgsmetoder, vedligeholdelsesindtægter og tankning (genopladning). Derfor undersøger artiklen behovet for at vedtage nye systemkonfigurationer, der skal maksimere fordelene ved elbiler, og som kan fremskynde deres udbredelse. Denne artikel introducerer derfor systemeffekterne i forbindelse med udbredelsen af elbiler fra et forretnings- og forsyningskædemæssigt perspektiv.

Den sjette og sidste artikel i denne ph.d.-afhandling (*Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark*) giver ligeledes svar på forskningsspørgsmål 3 (*Hvad er systemets indvirkning på elektriske køretøjer og V2G-teknologien?*) ved at undersøge de sociale omkostninger og fordele ved elektriske køretøjers forskellige systemkonfigurationer både med og uden brug af V2G. Til dette formål præsenterer artiklen fire forskellige scenarier med udgangspunkt i den nuværende energiforsyning i Danmark sammenholdt med energiforsyningen i 2030. Scenarierne inkluderer bl.a. potentialet for el-køretøjer i den offentlige flåde samt kommunikationsevnen (dvs. intelligent opladning eller V2G) sammenholdt med forskellige tilgange til energiimplementering i fremtiden.

Artiklen beregner derefter de mulige samfundsmæssige omkostninger for alle scenarier, herunder kulstof- og sundhedskilder for at finde den mest omkostningsminimerende løsning til at få flere elbiler ind på markedet. Artiklen konkluderer, at den mest omkostningsminimerende løsning i nær fremtid er 27%, og stiger til 75% i 2030, hvilket vil være en reduktion på 34 milliarder dollars i samfundsomkostninger i 2030; et fald på 30% i forhold til et traditionelt forretningsscenario. Men de ugunstige markedsforhold, som elbiler stadig er oppe imod, herunder økonomiske forskelle eller manglende betalingsvilje kombineret med rabatter til forbrugeren, udgør stadig betydelige barrierer for udbredelsen af elektriske køretøjer i Danmark. Denne artikel undersøger derfor systemets indflydelse på elbiler og V2G samt fremhæver deres potentiale for udbredelse.

Denne ph.d.-afhandling præsenterer således ovenstående seks artikler med det formål at besvare de tre forskningsspørgsmål ud fra en ’mixed-metholds’-tilgang, der omfatter både kvantitative og kvalitative metoder samt en tværfaglig og holistisk tilgang til at forstå de sociotekniske elementer, der ligger til grund for udbredelsen af elbiler og V2G-teknologien. Afhandlingen uddyber og konkluderer med et ’roadmap’, der giver et bud på elektrisk mobilitet i fremtiden, herunder specifikke løsninger til, hvordan elbiler kan fremstilles, markedsføres og udbredes bredt i samfundet med henblik på at udnytte deres potentiale til at reducere CO_2-udledningen.

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List of acronyms and abbreviations

BEV – battery electric vehicle

EVs – electric vehicles

EVSE – electric vehicle supply equipment

ICEV – internal combustion engine vehicle

OEM – original equipment manufacturer

PHEV – plug-in hybrid

V1G – one way communication vehicle-to-grid

V2G – vehicle-to-grid

WTP – willingness-to-pay

1. Introduction

This first chapter provides the structure of the research as well as a general overview of the dissertation, followed by the motivations of research. Then, the document elaborates on the research questions and applied methodology, including elements such as research philosophy and design. Finally, the chapter elaborates on the contributions and novelty of the research presented on this PhD dissertation.

1.1 Dissertation structure

This PhD dissertation is structured across three thematic elements representing levels of analysis for the diffusion of electric vehicles: consumer and retail level, meso-level, and system wide implications. This follows the notions of Sovacool, Axsen, et al. (2018) in seeking a cohesive and coherent macro structure to the research project. Each level presents a specific research question based on a socio-technical perspective of the electric mobility space and how this technology interacts across systems in society. To provide answers on how electric vehicles (EVs)[1] and vehicle-to-grid (V2G)[2] are currently and will continue to penetrate society, this dissertation introduced six scientific articles that address different elements of each research question. The structure is presented in Table 1.

Theme	Research Question	Article Title	Authors	Journal	Year
Consumer and retail level	**(RQ1)** How are electric vehicles diffused in the retail and consumer level?	**(1)** Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale	Zarazua de Rubens, Gerardo, L Noel, and BK Sovacool	Nature Energy	2018
		(2) Who will buy EVs after early adopters? Using machine learning to identify EV mainstream buyers and their characteristics	Zarazua de Rubens, G	Energy	2018
Meso-level	**(RQ2)** What are the structural barriers and benefits of electric vehicles	**(3)** Understanding the Socio-technical Nexus of Electric Vehicle (EV) Barriers: A qualitative discussion of Range, Price, Charging and Knowledge	Noel, L., G. Zarazua de Rubens, J. Kester, and BK. Sovacool	Energy Policy	2018

[1] In this PhD dissertation, its methods and results, when referring to electric vehicles (EVs) it considers both battery electric vehicles (BEVs), or 100% electric, and also plug-in hybrid vehicles (PHEVs), unless when explicitly noted.
[2] Vehicle-to-grid (V2G) technology is the technical capability of electric vehicles that allows for a dual flow of communication and power, in other words it enables bi-directionality. Through this ability, V2G-capable EVs open a range of new opportunities and provide electric grid services, along with other new potential applications.

	and vehicle to grid?	**(4)** Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)	Noel, L, Zarazua de Rubens, G, Kester, J & Sovacool, B.	Transport Policy	2018
System wide implications	**(RQ3)** What is the system impact of electric vehicles and vehicle to grid?	**(5)** The market case for electric mobility: Investigating electric vehicle business models for mass adoption	Zarazua de Rubens, G., L. Noel, J. Kester, BK. Sovacool	Energy Policy	2018
		(6) Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark	Noel, L, Zarazua de Rubens, G & Sovacool, BK	Energy	2018

Table 1. PhD dissertation structure.

Considering the structure presented in Table 1, the PhD dissertation is then arranged across the three thematic elements, each representing a chapter, and including two scientific articles in each chapter. The last section then introduces a discussion chapter to elaborate and conclude this dissertation by synthesising results to produce insights of each chapter, as well as presenting a prospective roadmap for EV and V2G diffusion. This dissertation also draws insights from the pool of various other articles that have been submitted and published as part of this PhD project but are not included in full, and act as complementary work to the selected research questions (RQ1, RQ2 and RQ3). This complementary pool of articles can be found in Appendix 6.1 of this document.

1.1 Motivation

The acknowledgement of climate change as the most pressing issue of this century has seen a global push to decarbonise society, with a strategy of targeting specific sectors starting with the electricity systems, followed by transportation and building infrastructure (i.e., heat energy). A low carbon power system can collaterally benefit the transport and building sectors, highlighting the benefits of cross-sector electrification (Benjamin K. Sovacool, Noel, Kester, et al. 2018). In particular, the electrification of passenger transportation can lead to more resilient cities, improve the efficiency of the distribution network and grid balancing capabilities, as well as reduce negative externalities such as pollution (Noel, Zarazua de Rubens, Kester, et al. 2018; Benjamin K. Sovacool, Noel, Kester, et al. 2018). For these reasons, electric vehicles have become the most prominent technology for the decarbonisation of passenger transportation (Kennedy et al. 2014; Needell et al. 2016; Richardson 2013; Muneer et al. 2015).

This potential for decarbonisation is agreed upon globally, with at least fourteen countries setting national EV deployment targets between 2020 and 2030 (International Energy Agency 2018) with

China aiming for 35 million by 2025 (Reuters 2017). National efforts for the decarbonisation of transport and support of EV technology have been further evidenced with Norway, France, the United Kingdom and India planning on implementing a ban of petrol and diesel vehicle sales as early as 2030, and China expected to follow in the short-term (Petroff 2017; BBC 2017). Industry-wise, most automotive manufacturers have at least one BEV or PHEV model within their product lines, and some traditional brands stating their production will only include electric models by the end of this decade (The Guardian 2017). At a retail level, the automotive market continues to see increases in the share of EV sales across many countries; here Norway still leads the way having 1 in 3 vehicles being full electric (Eafo 2017).

From a scientific and academic standpoint, the momentum around EVs is evidenced in the number of EV and V2G publications across the last decade (Figure 1), where EV publications have increased from ~8,500 in 2008 to over 42,000 new publications in 2018, and for V2G from less than 500 to almost 3,000 new publications across the same time frame.

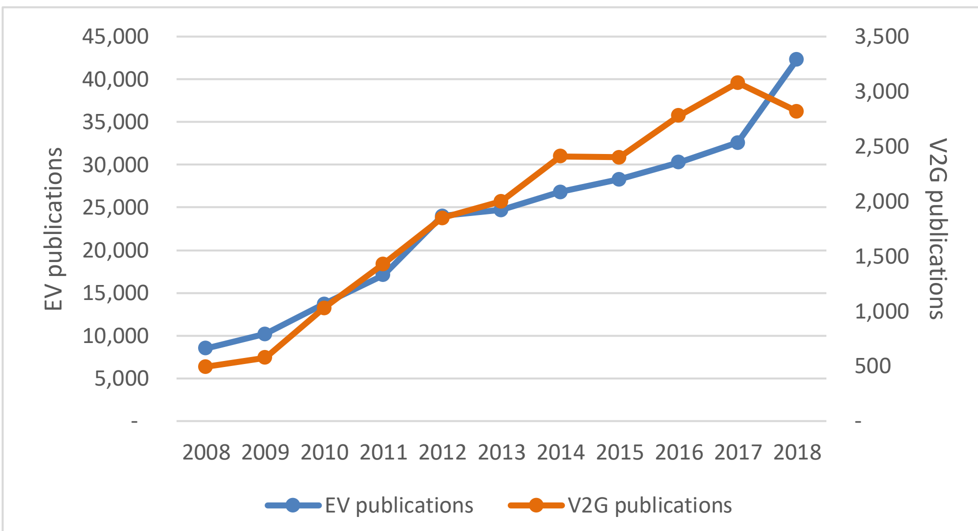

Figure 1. Number of electric vehicle (EV) and vehicle-to-grid (V2G) publications 2008-2018 (TYD). Note: Constructed by Author based on Google Scholar outputs.

While the momentum around EVs is building with the total global demand exceeding 3m EVs on the roads in 2017, the stock of EVs remains at around 0.2-0.3% of the total global passenger fleet (International Energy Agency 2017; International Energy Agency 2018). Moreover, as seen in Figure 2, while at a European level progress has been made in particular in Iceland and Norway, the continent as a whole only has achieved a market share of ~2%; meaning only two out of every one hundred new sold cars in 2018 is either battery electric or plug-in hybrid. Hence, society is still introducing ~98% of all new cars fuelled by petrol or diesel.

Figure 2 also shows that the transition to electric mobility has been unequally distributed across countries, showing that there continues to be structural barriers that prevent electric vehicle adoption, even in countries with arguably good conditions for EVs to prosper, such as Denmark – with high socio-economic indicators, more than 50% low carbon electricity system, dense population settlements and even a legacy of green technologies with the well-developed wind Danish sector (Table 2).

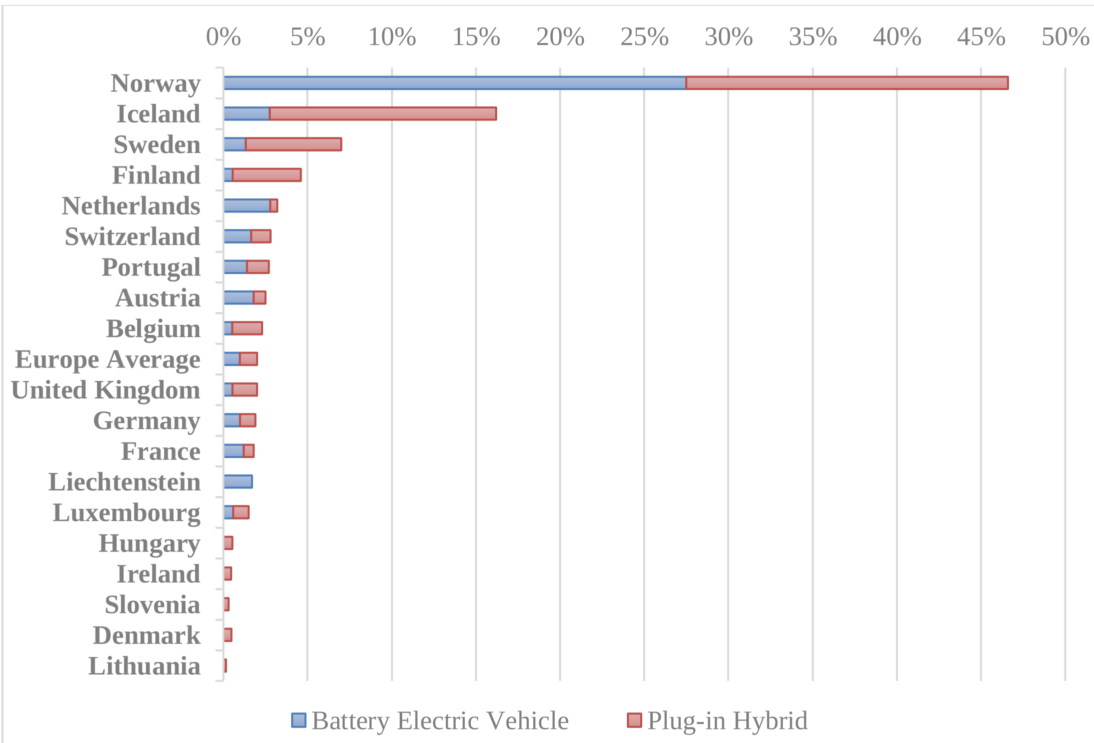

Figure 2. Electric vehicle market share in Europe Q1-Q2 2018, top 20 countries. Note: Constructed by Author with data from the European Alternative Fuel Observatory (EAFO). Data includes battery electric vehicles and plug-in hybrids. The EAFO is under current website maintenance.

	Iceland	Sweden	Denmark	Finland	Norway
Population **(Mln.)**	0.35	9.9	5.73	5.49	5.2
Sq. km **(thousand)**	103.0	447.4	42.9	338.4	385.2
Population density **(thousand p/sq km)**	3.3	24.3	135.6	18.1	14.3
GNI per capita **(US$)**	53,280	50,980	52,390	45,400	63,980
CO2 emissions **(metric tons per capita)**	6.08	4.62	6.78	8.51	11.74
Non-CO2 electricity	99% (hydro 73%, geothermal 27%)	98% (nuclear 35%, hydro	Over 60% (wind 49%, bio & waste 12%)	78% (nuclear 34%, hydro	98% (hydro 96%, wind 2%)

production (% of total)		46%, wind 10% and bio & waste 7%)		24%, bio & waste 16%, wind 3%)	
Relation to EU	EEA member	EU member	EU member	Eurozone member	EEA member
Average age of passenger car fleet	10.6 years	9.6 years	8.5 years	12.7 years	10.6 years
Passenger car taxation	Excise duty and weight differentiated registration tax. Annual ownership tax based on weight	Primarily CO2 and weight differentiated yearly ownership tax (no registration tax)	Primarily one-time value-added registration tax Annual ownership tax based on fuel consumption	Annual vehicle tax based on CO2 emissions and weight	Registration tax based on weight, engine and emissions. Fixed annual ownership tax.
EV sales share (April 2018)	16.20%	7.00%	0.90%	4.60%	46.60%

Table 2. Overview of the five Nordic countries. Note: Table adapted from (Kester et al. 2018a)

At the same time, the diffusion of V2G has faced even more challenges. While it has been argued that V2G integration in EVs would provide substantial benefits (Lund & Kempton 2008; Benjamin K. Sovacool, Noel, Axsen, et al. 2018), there has been even less research and tangible implementation. For example, in the Nordics, there is only one small pilot project in Denmark, despite other EV successes elsewhere. In total there are only a few hundred V2G capable EVs sprawled across a handful of pilot projects around the globe (Noel et al. 2019). In short, while there appears to be a litany of benefits related to both EVs and V2G, their diffusion has stagnated below what would likely be societally optimal, leading to recent articles focusing on what barriers need to be removed in order to reach higher levels of EVs and V2G (Noel et al. 2019).

The main motivation of this PhD project and dissertation is therefore to further the transition and adoption of EV and V2G technologies in wider society, in order to capture their entire array of benefits and value, ultimately contributing to social decarbonisation and alleviate the pressing challenge of climate change. The Nordic region is considered as the place of study, as these countries offer both an environment in which EVs are already making some progress, as it is evidenced through both Figure 2 with already four of the highest EV penetration rates in Europe; but also as these are well-developed economies with a legacy of socio-economic wealth and progressive environmental agendas (Benjamin K. Sovacool, Noel, Kester, et al. 2018; Benjamin K. Sovacool, Kester, et al. 2018). Hence, the Nordic region provides the perfect setting in order to conduct research and further investigate the barriers and benefits of EVs and V2G, which this dissertation does through its three research questions; while, allowing to use the lessons for other countries or markets wanting to implement and EV or V2G transition. At the same time, this PhD project also offers a roadmap for technology diffusion, where the lessons of this dissertation can be extrapolated to other technological settings, particularly around low carbon technologies such as smart meters, solar kitchens or energy storage.

1.3 Research questions

Considering the main thematic foundation of this PhD dissertation in investigating the feasibility of EVs and V2G in the Nordic region, the research has sought to capture the knowledge-creation processes and outcomes that would optimise value creation and impact for academia, but also for industry, consumers and decision-makers. Thus, following the notions presented in Sovacool, Axsen, et al. (2018) in designing research questions that add value to academia and beyond, but also in providing rigor, quality and feasibility to the research project. For this purpose, the research established a main overarching question, supported by specific three research questions. The main question of this research is:

What are the socio-technical challenges, benefits and potential of electric vehicle and vehicle-to-grid diffusion in wider society?

This main question intends to provide a socio-technical approach to the system analysis of the penetration of EV and V2G technology across different levels. In order to holistically capture the nuance of the EV/V2G system, the research is divided across three specific research questions, the first of which being:

Research Question 1: How are electric vehicles diffused in the retail and consumer level?

In order to answer this question, the research introduces the analysis of two perspectives: the retail and the consumer level. The first one refers to the space in which industry and consumers meet at the market place, in other words, the point of engagement between supply and demand. Through this analysis this question explores potential disconnects in the automotive vehicle supply chain that may be preventing EV penetration in national fleets. The second element of this question looks at the consumer space, focusing on the prospective pool of automotive consumers. The focal point is to understand the consumer space in relation to electric mobility to identify the market potential of the technology, but also to identify strategies to reach these potential consumer markets. As a whole, these two elements relate to the main thematic foundation of this dissertation by exploring the end-point in the automotive supply and selling chains, to explore the technology path of adoption. Next, the second question discusses the meso-level of EV and V2G, exploring the contexts of benefits and barriers:

Research Question 2: What are the structural barriers and benefits of electric vehicles and vehicle to grid?

The second question aims to explore the full array of both challenges and benefits that arise in introducing EV and V2G technology, focusing on current and future scenarios/cases. Through this question the dissertation not only furthers the current academic literature by looking at the entire spectrum of barriers and benefits, but also provides visibility and foresight for industry and other interested actors into what elements of the EV and V2G may result a challenge or benefit in the near, mid and long term. Therefore, this question allows this dissertation to provide scope into the path for EV diffusion. Finally, moving to the third research question, the scope expands to the macro-level of how an EV and V2G transition would impact the societal system:

Research Question 3: What is the system impact of electric vehicles and vehicle to grid?

In researching this question, the dissertation aims to provide insights into the system effects of EV and V2G diffusion from two perspectives: first, the business and supply chain, and second, the system integration of EVs and their social impact. In this way, this question investigates the implications of an electric vehicle transition, and how this technology can transform existing system architectures. Therefore, this question opens the scope of analysing EV and V2G diffusion and their social impact.

Thus, the PhD dissertation has as research objective to investigate the pathways of diffusion for EV and V2G, focusing particularly on the Nordic region. The aim is to analyse the transition to electric mobility across three system levels looking at the consumer and retail space, the structural challenges and benefits of EVs and V2G and the system effects of these electric vehicle technologies. In the next section, this dissertation elaborates on the applied methodology to reach the stated objectives.

1.4 Methodology

In this section, this dissertation introduces the selected and applied methodology for researching the research questions described above. It first discusses the research philosophy and the foundation of the methodological approach. In turn, it then shows the selected research design and finalises the methodologies used in each of the six articles presented on this dissertation.

1.4.1 Research philosophy

In delimiting the philosophical approach to conducting research, this dissertation aims to present the lens through which reality is understood by defining a set of ideas and how these shape the approach to research (Creswell 2014; Saunders et al. 2009). In doing so, research involves a number of assumptions about human knowledge, or epistemological assumptions, about realities encountered, ontological assumptions, and the self-assumptions of influence, axiological assumptions (Saunders et al. 2009). Often beliefs and lens of the researcher results in adopting specific methodological approaches, whether qualitative, quantitative or mixed methods. Despite an ongoing debate in the literature regarding research philosophy, Creswell (2014) notes four main positions in postpositivism, constructivism, transformative and pragmatism. Each of these strands of research is arguably better suited for specific methodological approaches, as it guides the researcher in the use of tools and methods to capture inputs from reality, while engaging in a process of analysis and understanding.

A postpositivist positioning is a commonly-used lens when conducting research, and in particular when implementing a scientific method in understanding reality, where the researcher challenges the traditional conceptions of an absolute truth of knowledge and reality (Howell 2013; Creswell 2014). Thus creates a testing environment where, through a deterministic philosophy, postpositivist research intends to determine the causes that influence outcomes; thus, alluding to quantitative research methodologies. In looking for answers to this dissertation's research questions, a postpositivist approach would allow the research to observe and measure the objective reality that exists, by using quantitative methods such as surveys or model-based approaches to understand reality.

On the other hand, a constructivist positioning is typically associated with qualitative methodologies, as it intends to understand the complexity of reality and its multiplicity, as opposed to focus on narrow meanings, categories, ideas (Creswell 2014). Hence, a constructivist approach intends to construct meanings through the engagement with the reality being interpreted and would allow the research presented on this dissertation to understand a reality that is not fully defined by using a combination of interpretations to construct answers in the investigation of the feasibility of EVs and V2G.

While both postpositivist and constructivists approaches would bring unique perspectives to the research questions of this dissertation, the foundation of the investigation occurs in a sociotechnical system where technological development and society mutually interrelate, arguing for co-evolution, and thus bringing complexity in the analysis and understanding of the system (Geels et al. 2008). For this reason, a pragmatic positioning is selected as this would allow to explore reality derived from actions, situation and consequences as opposed to solely on antecedent elements (Creswell 2014; Gray 2018), considering the newness of and constant change in the electric mobility space. In doing so, pragmatic approaches would call for the utilisation of a variety, if not all, approaches available to understand a problem, therefore calling for a mixed methodology design. Reality would not be considered as an absolute unity, thus its understanding is created through the collection and analysis of different data, both quantitative and qualitative, as opposed to a single method (Saunders et al. 2009). Notably, pragmatic positionings have been criticised as the research can result an unstructured application of mix methodologies, driven by the expectancy of outcomes and resulting in distorted views of reality (Lawler & Mahoney 1998; Tashakkori et al. 1998). Therefore, this research also follows the notions of critical multiplism (Patry 2013), in the triangulation of data and research inputs in mitigating the risks of biases in the interpretation of reality and validating the understandings created through this research project.

1.4.2 Theoretical foundation and Mixed methodology

This dissertation is based on a sociotechnical approach considering the space in which electric mobility operates, at the nexus of electricity and transport systems, as well as its technological development. As such, the sociotechnical perspective is a complex view on the relationships of technology and social development, where these co-develop and interact in mutual evolution (Geels et al. 2008; Cherp et al. 2018). For this dissertation, a sociotechnical analysis is also relevant because it is founded in innovations that occur outside of existing dominant regimes, in this case the transition to electric mobility in the automotive sector. Moreover, the approach considers that sociotechnical dynamics are multi-dimensional (Geels et al. 2008), with the interaction not only across different systems, but also individuals, artefacts and levels within and between each system; therefore the insights from different disciplines are key to understand processes within the elements of a sociotechnical system. In doing so, the sociotechnical perspective draws insights from social, political, culture, technical and environmental processes, as well as investigates the system itself. For this reason, this dissertation adopts a mixed method approach for the investigation of the socio-technical system in which electric mobility operates, develops, interacts and evolves.

Mixed methodology research designs originated with the premise that all methods have a bias and particular weaknesses, where the collection of both qualitative and quantitative data allows to mitigate those risks (Creswell 2014). In turn, the multi-method approach validates the data through triangulation, discovering unique insights, creating better measuring instruments, and its own database (Creswell 2014). In providing answers to the research questions (see Table 1 above), this dissertation presents a mixed method approach that includes primary methods of data collection, such as: a) semi-structured expert interviews, b) online survey, c) mystery shopping and d) empirical datasets, which are described further below. Secondary methods were also utilised based on peer-reviewed literature and other available second-had sources of data, such as market reports.

In sum, the research follows a convergent parallel mixed method approach. It is argued that studies in this configuration combine data collection processes of qualitative and quantitative data to subsequently provide more meaningful analysis and outputs (Creswell 2014). Hence, this dissertation makes use of both data elements to in the investigation of the roadmap for EV and V2G diffusion, focusing particularly in the Nordic region. Notably, the six articles presented on this dissertation follow specific approaches to answer specific elements of each of the three research questions. Next the four main methodologies used on this PhD project are explained, and subsequently on the next section (1.4.3 Research design) the dissertation elaborates further on how these methodologies are applied in each article.

a) Semi-structure expert interviews

First, this PhD dissertation draws data from an original set of 227 interviews conducted with 257 experts from 201 organisations of the transportation and electricity sectors across the five Nordic countries of Denmark, Finland, Iceland, Norway and Sweden. This method allows for the comprehensive and in-depth discussion of complex and multi-connected topics, that includes the integration of an individual's perception, attitudes and values (Harrell & Bradley 2009; Yin 2013), as the method provides flexibility in the data collection process by creating a conversational channel of information-gathering that allows space for spontaneous responses, adding narrative to the research (Harrell & Bradley 2009; Leavy 2014). Admittedly, there are potential biases and limitations in conduction of this research method such as self-selection bias, level of expertise across the respondent sample, and the potential to influence outcomes (Kester et al. 2018a; Noel, Zarazua de Rubens, Kester, et al. 2018).

The interviews lasted between 25-90 minutes and were primarily conducted in person. Interviews were recorded with one exception (but thorough notes were taken). The recordings were fully transcribed and thereafter coded in NVIVO following an inductive, grounded approach (Benjamin K Sovacool et al. 2018), where nodes and themes are created based on arguments. Respondents are anonymised and were given an identification number (respondent one = R1, etc.). An overview of the respondents is provided in Appendix 6.3, and in Appendix 6.4, the sample is broken down by interview ID. The collection of this data was conducted by the authors of the third, fourth, and fifth articles presented in this dissertation (for author contributions please refer to Appendix 6.2).

b) Online survey

Next, the dissertation also includes an original dataset in the form of an online survey that was anonymous and available from September 2016 to November 2017. The survey was distributed both in a randomised sample and a non-random sample. The random sample was collected by the survey consulting firm Qualtrics across the five countries, with the aim to be representative of the Nordic populations. On the other hand, the non-random sample was used to target specific subpopulations, such as current EV owners or rural Icelanders. Together, both samples totalled 5,894 responses. Many completed surveys were only partially filled in, and these are excluded in the analysis presented in this dissertation. Thus, the total respondent number used for the analysis is 5,067. The survey consists of four sections (Appendix 6.5): Vehicle History & Background, 2) Vehicle Preferences, 3) Electric Vehicle Choice Experiment, and 4) Demographics. The choice experiment is not reported on in this dissertation.

The survey design provides a quantitative description of a population's trends, attitudes, interests or opinions through the study of a particular sample of the respective population (Creswell 2014). Survey-based methodologies are thus commonly used in transport and energy-related studies, for example, recent research looking into the energy and environmental attitudes in Denmark (Sovacool & Blyth 2015) In doing so, the survey approach allows to generalise from sample specific elements of a population, and in this case, it serves for analysing the prospect of EVs and V2G in the Nordic region. However, such generalisation can also result in sample biases and misrepresentations of reality, especially if there are errors in the survey's assumptions or sampling and thus, this dissertation makes use of non-random samples across the investigated countries.

c) Mystery shopping

This dissertation includes an innovative method in the investigation of EV and V2G diffusion. For this purpose, 126 car dealerships were visited for mystery shopping between October 2016 and June 2017 across 15 cities in the countries of Denmark, Finland, Iceland, Sweden and Norway. The aim of the method was to engage with sales staff as customers, enquiring about vehicle options and purchasing advice, with the aim to obtain insights of the sales strategies of dealerships, attitudes towards particular vehicle types, existence, intent and level of influence when trying to sell an electric vehicle. The visits followed a "mystery shopper" approach (Wilson 1998) to test the consumer experience when purchasing a vehicle at a car dealership, where these should be a basic enquiry that needs no follow-up, leaving no lead for serious purchase (Wilson 1998). In doing so, the shopping experiences were fairly short, usually 10 minutes, where the shoppers did not show any initial orientation towards EVs and instead allowed the salesperson to guide the sales conversation. The combination of these two elements allowed the applied method to mitigate some of the ethical concerns of mystery shopping (Kwet Shing & Spence 2002; Finn & Kayandé 1999). The shopping encounters were then anonymised (see Appendix 6.6).

This method included both qualitative and quantitative elements of data collection. After each dealership visit, the mystery shoppers recorded three sets of data into an audio file: the responses to the dealership visit questionnaire, dealership characteristics, and notes on their shopping experiences including individual thoughts and relevant quotes from the salesperson. Please refer to section 2.1.2 for further discussion on this method and its application.

d) Other methods

The PhD dissertation also makes extensive use of peer-reviewed literature across all stages of the research process. In doing so, it follows the notions of Punch (2013), where a review of the literature supports the pre-empirical phase of the research, and also the recommendations of Creswell (2014), for validating the use of multi-method approaches. The literature has been investigated via well-established data bases such as Google Scholar, and via Danish Bibliometric Research Indicator 2 (BFI-2) and Danish Bibliometric Research Indicator 1 (BFI-1) recognised journals including Applied Energy, Energy Policy, Transport Policy, Transportation Research Part A-D, Global Environmental Change, Nature Energy, among others. In addition, this dissertation made extensive use of secondary sets of information and data primarily available through well recognised sources such as the International Energy Agency (IEA), European Alternative Fuels

Observatory (EAFO) and European Union reports. Data from these sources is presented across the six articles introduced on this dissertation.

1.4.3 Research design

The design of research of this dissertation follows a multi-method approach in order to provide insights and depth of the generated knowledge, as well as to follow the notions of sociotechnical investigations that operate in multidisciplinary settings. In doing so, it recognises the work of Sovacool, Axsen, et al. (2018) matching specific methods of research with desired objectives. Below this dissertation presents the research design of each article, which is introduced in this thesis to provide answers to the research questions. Table 3 provides an overview of the research design.

The first article investigating the automotive retail space was designed based on a convergent parallel mix method approach where both quantitative and qualitative data elements are collected at the same time, for subsequent integrations and interpretation of findings (Creswell 2014). The methodology approach is based on the use of 126 car dealership visits across 15 cities in the five Nordic Countries of Denmark, Finland, Iceland, Norway and Sweden. The visits were conducted using a mystery shopping approach where researchers take the role of consumers in exploring the engagement with the supply side. This included both a qualitative and quantitative component of data collection (see section 2.1.2.1). To ensure validity, this method was triangulated with 30 expert interviews from the transportation and electricity sectors. These interviews were taken out of a pool of 227 interviews with 257 expert participants on electric mobility more broadly in the region. For an overview of this sub-sample of interviews, refer to Appendix 6.6. Secondary data was also use in the form of peer-reviewed literature and other data, such as vehicle statistics. The design followed the premise of sociotechnical studies in the understanding of multidisciplinary systems, and thus data triangulation in a multi-method setting was used to ensure validation of results.

The second article uses primary metho data from an online survey (n = 5067) across the five Nordic countries, based on demographic and socio-economic characteristics, mobility and vehicle preferences, and stated EV and V2G interests. Survey-based studies are a frequent tool in both qualitative and quantitative studies across transportation and energy research field (Strengers & Maller 2014; Sovacool & Blyth 2015). This study also draws on the popular theory of diffusion of innovation, referring to the different types of consumer profiles according to specific stages of technology adoption (Rogers 2003). The survey is then analysed by using a machine learning model, based on the k-means method. This method is a data-driven approach that uses an unsupervised learning algorithm to understand patterns and insights within the dataset. The outputs are then validated with secondary data such as peer-reviewed literature and transportation data.

The next three articles have as primary method the use of semi-structured interviews with experts in the transport and electricity sectors. The total sample included 227 interviews with 257 experts of the selected industries, across 17 cities in Denmark, Finland, Iceland, Norway and Sweden. During the interviews questions targeted selected themes and were subsequently explored according to the context of the interview. For the third article, experts provided answers to the question: *What are the set of barriers that electric vehicles currently face?* with subsequent follow up question as the interview developed. For the fourth article, experts provided answered to the question: *What are the full set of benefits that electric vehicles and vehicle-to-grid offer?* Also including subsequent questions as interviews evolved. The fifth article also used the set of interviews as its primary method, however, this article draws insights across the entire set and builds upon the results of the primary questions on EV and V2G (of articles 1 and 2), and on the commonality of the answers around the system impact of these technologies, from a business and supply chain perspective.

The sixth article utilised as its main data collection method the use of secondary sources of data, information and peer-reviewed literature. The sources of this data are well recognised bodies such as Statistics Denmark, European Alternative Fuel Observatory and European Commission. Data was then fed into an economic optimisation model created in MATLAB to find the least-cost mix of EV and V2G penetration in Danish society from the immediate future up until 2030. The model is based on collection of data for vehicle costs and grid costs, including social and environmental elements.

Theme	Research Question	Article No.	Subject researched	Data collection	Data Analysis
Consumer and retail level	(RQ1) How are electric vehicles diffused in the retail and consumer level?	1	The bottlenecks for EV diffusion at the automotive retail space	▪ 126 car dealership visits across ▪ 30 expert interviews ▪ secondary data (literature, market reports)	▪ Qualitative coding and analysis ▪ Descriptive statistics, Analysis of Variance, and regression
		2	The prospective EV mainstream market and their characteristics	▪ Online survey of ~5000 respondents from the 5 Nordic countries ▪ Peer-reviewed literature	▪ Descriptive statistics ▪ Cluster algorithm, k-means
Meso-level	(RQ2) What are the structural barriers and benefits of electric	3	The structural challenges for EVs and V2G	▪ 227 semi-structured interviews with experts of transport and energy sectors of the 5 Nordic countries ▪ Peer-reviewed literature	▪ Qualitative coding and analysis using NVIVO

	vehicles and vehicle to grid?	4	The array of benefits of EVs and V2G	▪ 227 semi-structured interviews with experts of transport and energy sectors of the 5 Nordic countries ▪ Peer-reviewed literature	▪ Qualitative coding and analysis using NVIVO
System wide implications	(RQ3) What is the system impact of electric vehicles and vehicle to grid?	5	The system business and supply chain system impact of EVs	▪ 227 semi-structured interviews with experts of transport and energy sectors of the 5 Nordic countries ▪ Peer-reviewed literature	▪ Qualitative coding and analysis using NVIVO
		6	The system impact of the optimal penetration level of EVs and V2G	▪ Market data ▪ Peer-reviewed literature	▪ Cost-optimisation model ▪ Descriptive data analysis ▪ MATLAB

Table 3. Overview of research design.

1.5 Contribution and novelty

The contributions of this PhD dissertation and the article it presents in answering its research questions can be analysed through the notions of Sovacool, Axsen, et al. (2018) based on the novelty, uniqueness and value of the research conducted. Here the research can be novel in three ways: theoretically, by contributing to the creation, testing, critique or revision of concepts, frameworks or theories; methodologically, by furthering and developing research methods; and empirically, by the applicability of methods or analysis of new types of data (Benjamin K Sovacool et al. 2018).

This dissertation provides novelty and contribution in the following ways. First, methodologically, the dissertation uses a multiple methods approach embedded in the research design, implementing both qualitative and quantitative methods in answering the research questions, totalling to four distinct methods (see section 1.4.2 above). The novel methodological contribution uses multiple approaches to answer complex questions, such as the ones within sociotechnical systems; in this case, electric mobility. Secondly, the dissertation employs innovative research methods, namely car dealership visits and mystery shopping for scientific enquiry. The value of this methodology was substantiated on the impact and reach of this study extending beyond the realm of academic circles and being discussed in social, industrial and decision-making circles.

Third, the novelty presented in this dissertation also includes the applications of its data to novel empirical settings. In particular, the dissertation collected a comprehensive sample data which can be considered difficult to attain, as is the case of experts and elites (Benjamin K Sovacool et al. 2018). In terms of data, the fourth novel contribution of this dissertation is the robustness of methods collected. Specifically, the dissertation includes 227 expert interviews with 257 participants across 17 cities in five countries, over 5,000 survey respondents across five distinct nations, and 126 car dealership visits across 15 cities in the Nordic countries. For comparability and evidence, other distinguish published studies in transport and energy have typically included samples of <30 interviews (Gallego & Mack 2010; Schliwa et al. 2015), <1,000 survey respondents (Sovacool & Blyth 2015) and <25 dealerships visited (Matthews et al. 2017). In sum, this dissertation utilises a mixed method data set that its orders of magnitude is larger than any other study only using one method.

Next, the fifth novel contribution is that, this dissertation presents data and insights across a unique international sample, consisting of five distinct national settings in Denmark, Finland, Iceland, Norway and Sweden. These countries have typically been positioned at the top of socio-economic indicators as well as being recognized for pushing aggressive decarbonization agendas within the energy and transport sectors (Sovacool 2017). Therefore, this research offers analysis across individual national settings but also offers regional comparability for validation and deeper insight into electric mobility. Finally, while the aim of this dissertation is not primarily to develop new theoretical conception or engage in critical theoretical discussions, it does provide novel theoretical contributions as defined by Sovacool, Axsen, et al. (2018). For example, the dissertation furthers existing theoretical notions within sociotechnical studies in the exploration of electric mobility and V2G, both of which are relatively new within the literature. In particular, the contributions underscore the importance of social aspects in the development of a technology, as it has been the social, not technical, systems around EVs that have tempered the transition. Moreover, the dissertation engages with diffusion of technology literature, providing a further understanding in how technologies diffuse across society, and especially the consumer aspects that are relevant for technology adoption.

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2. Theme 1: exploring the consumer and retail level

The first research question is answered by introducing the following articles:

1. Zarazua de Rubens, G, Noel, L & Sovacool, B 2018, '*Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale*' *Nature Energy*, vol. 3, pp. 501-507.

2. Zarazua de Rubens, G. (2018) '*Who will buy EVs after early adopters? Using machine learning to identify EV mainstream buyers and their characteristics'*. Under Review with Energy

The two journal articles intend to explore the consumer and retail space in which electric vehicles operate. The first article focuses on the point of sale of the automotive selling industry, to identify potential bottle necks in the diffusion of electric mobility. Whereas the second article focuses on the consumer space, exploring the potential consumer markets for the diffusion of electric vehicles, thinking of mass market adoption.

2.1 Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale

The first article presented in this dissertation investigates the automotive point of sale, and the role car dealerships play in the transition to electric mobility. It explores the strategies, methods and approach of car dealerships in promoting (or not) electric vehicles to prospective automotive consumers. In particular, as most consumers do not have pre-existing knowledge of EVs, and current market conditions favour petrol and diesel vehicles, car dealership experiences may strongly influence EV purchasing decisions. Here we show that car dealerships pose a significant barrier at the point of sale due to a perceived lack of business case viability in relation to petrol and diesel vehicles. In 126 shopping experiences at 82 car dealerships across Denmark, Finland, Iceland, Norway, and Sweden, we find dealers were dismissive of EVs, misinformed shoppers on vehicle specifications, omitted EVs from the sales conversation and strongly oriented customers towards petrol and diesel vehicle options. Dealer's technological orientation, willingness to sell, and displayed knowledge of EVs were the main contributors to likely purchase intentions. These findings combined with expert interviews suggest that government and industry signalling affect sales strategies and purchasing trends. Policy and business strategies that address barriers at the point of sale are needed to accelerate EV adoption.

2.1.1 Introduction

Electric vehicles (EVs) have great potential to contribute to the decarbonisation of society and help achieve national and international climate targets by reducing emissions of both the transport sector, which accounts for one fourth of energy-related global greenhouse gas emissions, and the electricity sector, via better integration and utilisation of renewable energy sources(Kennedy et al. 2014; Needell et al. 2016; Richardson 2013; Muneer et al. 2015; International Energy Agency 2017; Noel et al. 2017). In turn, a growing stream of research has explored the social, political and market implications and barriers to EV diffusion and use(Needell et al. 2016; Berkeley et al. 2017; Tran et al. 2012); from taxation and policy incentives (Mersky et al. 2016; Bakker & Jacob Trip 2013; Harrison & Thiel 2017), to consumer-focused studies (Vassileva & Campillo 2017; Egbue & Long 2012; Rezvani et al. 2015).

However, the retail relationships of the EV market, in particular the interaction between industry actors such as automotive original equipment manufacturers (OEMs), dealerships and prospective EV owners at the point of sale, have been under-explored. Dealers represent an important yet understudied intermediary between new innovations like EV technology and consumers. Only three North America-focused studies exist as of 2017. For instance, a California-specific (US) study suggests that EVs require new business and promotion strategies during sales processes (Cahill et al. 2014), where a study across four US States (Reports 2014) and an investigation in Ontario (Canada) (Matthews et al. 2017) find that the (lack) of salespersons EV knowledge and positive attitude can influence customers purchasing decisions. However, these studies either feature small sample sizes, lack cross country comparisons or focus on early EV adopters (Cahill et al. 2014; Reports 2014; Matthews et al. 2017).

Despite this dearth of research coverage, the role of industry actors is important because research suggests that current EV buyers can be categorised as early adopters with a higher technological acumen and knowledge of EVs (Axsen et al. 2016; Axsen et al. 2015), implying that they may aggressively and actively pursue EVs at the selling point. Early adopters, however, are a minority of the total market. Therefore, car dealerships and EV purchasing experiences at the point of sale may be where a majority of consumers first encounter the technology and also consider purchasing it.

For this reason, we investigate the prospect of purchasing an EV from the perspective of an average or mass market customer in 126 dealership shopping visits at 82 car dealerships across 15 cities in the five Nordic countries (Denmark (DK), Finland (FI), Iceland (IS), Norway (NO) and Sweden (SE)) triangulated with industry stakeholder interviews across these countries. We also analyse the effect of location-specific factors on EV purchases, such as the comparison between urban and rural settings, and the different tax, regulatory, commercial and social conditions of each country. This includes comparisons between the EV global leader Norway, an intermediate adopter (SE), and less developed EV markets of FI, IS, and DK. The latter is the first country to reintroduce taxes on EVs (European Automobile Manufacturers Association 2017; Levering 2017).

Our results indicate that national policy and signalling, both from government and industry, substantially affect the EV purchase likelihood at the point of sale. Although all the investigated countries are known for being international leaders in the area of energy and climate policy and have various EV incentives in place, we find these are ephemeral when compared to petrol and diesel vehicle incentives, with the exception of Norway. Thus, EVs tend to be a comparably less attractive option both for the dealership to sell and the customer to buy. As a result, these unfavourable market conditions for EVs are in turn reflected in dealer sales strategies, where we find a lack of willingness to sell EVs to mainstream customers.

2.1.2 Research approach

Our research team posed as "mystery shoppers" and therefore remained neutral and showed no initial inclination to any particular type of passenger vehicle. This neutral approach tests the direction and level of orientation in which sales personnel guide mainstream customers to or away from EVs. To ensure validity, the shopping encounters were triangulated with 30 expert interviews with major automobile manufacturers, importers and associations, and other related organisations such as EV charging stations providers across the Nordic region. These interviews were taken out of a pool of 227 interviews with 257 expert participants on electric mobility more broadly in the region (Kester et al. 2018b; Benjamin K. Sovacool, Kester, et al. 2018). We refer to the mystery shopping experiences by visit number (e.g., V12) and the interviews by respondent number (e.g., R22).

2.1.2.1 Mystery Shopper Approach

This study was designed to investigate experiences and perceptions at the point of sale from the perspective of an average, or mass market, consumer and assess the likeliness of an ordinary person choosing to purchase an EV as opposed to a petrol or diesel vehicle (EV purchase likelihood). Researchers visited car dealerships and engaged with sales staff as customers, enquiring about vehicle options and purchasing advice, with the aim to obtain insights of the sales strategies of dealerships, attitudes towards particular vehicle types, existence, intent and level of influence when trying to sell a vehicle. We used a "mystery shopper" (Wilson 1998) approach to test the consumer experience when trying to purchase a vehicle at a car dealership. The shopping visits followed suggestions of Wilson, who infers that mystery shopping for car dealerships should be a basic enquiry that needs no follow-up, and leaves no lead for serious purchase (Wilson 1998). The mystery shoppers—two of the authors (male adults, ages 26 and 34)—did not show any initial orientation towards EVs and rather allowed the salesperson to guide the sales conversation. More specifically, the study intended to measure if EVs were included within the sales conversation and the direction (positive or negative) of the advice given regarding EVs.

We visited 126 car dealerships between October 2016 and June 2017 across 15 cities in the countries of Denmark, Finland, Iceland, Sweden and Norway. The visits where conducted typically in the capital, the second most populous city and the largest rural town of each country: Aalborg (Denmark), Aarhus (Denmark), Akureyri (Iceland), Copenhagen (Denmark), Gothenburg (Sweden), Helsinki (Finland), Malmo and Lund (Sweden), Oslo (Norway), Oulu (Finland), Reykjavik (Iceland), Stockholm (Sweden), Tampere (Finland), Tromsø (Norway), and Trondheim (Norway). Dealerships varied in whether they were brand-specific or multi-brand, and whether they were EV-certified and non-EV-brand dealerships.

Following the mystery approach (Wilson 1998), the shopping visits were fairly short experiences, usually 10 minutes. This approach allow us to mitigate some of the ethical concerns of mystery shopping, especially since the researchers themselves showed no intention of purchasing a vehicle (Kwet Shing & Spence 2002; Finn & Kayandé 1999). The shopping encounters were anonymised (see Appendix 6.6). To mitigate potential biases and ensure representativeness of the study shopping visits spanned a distribution of times of day (across dealer's working hours, 9:00-17:00), dealership types (multi-brand and brand-specific dealers, as well as EV certified and non-EV certified), two mystery shopper profiles, and geography (15 cities in 5 different countries). Pilot testing was conducted at one dealership per country visited to assess local conditions. The mystery shoppers did not show any initial orientation towards EVs and rather allowed the salesperson to guide the sales conversation.

After each dealership visit, the mystery shoppers recorded three sets of data in an audio file including the responses to the dealership visit questionnaire, dealership characteristics, and notes on their shopping experiences including individual thoughts and relevant quotes from the salesperson. Promotional material provided by dealers (leaflets and price lists), dealer's business card and in some cases photographs of advertisement, charging infrastructure and dealership location were also collected.

2.1.2.2 **Dealership visit evaluation criteria**

To understand the dynamics at the automotive point of sale, mystery shoppers completed a five-item questionnaire (evaluation criteria) after each visit (Table 4) to assess the Salespersonship Quality, ICEV Orientation, EV Orientation, EV Knowledge and EV Purchase Likelihood for each of the car dealership visits. Salespersonship quality was assessed based on the salesperson's perceived professionalism, attitude, enthusiasm and ability to sell and service the customer(Curry 1992). Technological orientation was assessed based on the direction and strength of steering into either ICEVs or EVs (ICEV Orientation and EV Orientation). This was based on the sales advice, promotional material provided, the inclination and willingness of the salesperson to promote either technology. Displayed EV knowledge was evaluated in terms of the amount and accuracy of information provided, regardless of whether it communicated positive or negative EV attributes. Lastly, based on the overall shopping encounter, and considering all experienced dynamics, the mystery shoppers assessed the likelihood of considering an EV purchase for their next vehicle after each dealership visit. Each item was rated on a 5-point Likert scale in 0.5-point increments.

Attribute	Question
Salespersonship Quality	How good was the perceived quality of dealer based on his/her sales approach? (e.g. perceived attitude, enthusiasm, professionalism and ability to sell)
ICEV Orientation	How much did the dealer orientate you towards an ICEV?
EV Orientation	How much did the dealer orientate you towards an EV?
EV Knowledge	How much knowledge did the dealer display about EVs?
EV Purchase Likelihood	After the visit, how likely would have you opted to purchase an EV as your next car?

Table 4. Qualitative evaluation criteria to assess interactions and experiences with electric vehicles at the point of sale. Note: Details the five questions mystery shoppers ranked after each dealership experience.

2.1.2.3 **Dealership visit variables**

We recorded nine variables for each of the 126 visits conducted (Table 5). The country and city of each dealership were recorded to determine if and how market conditions impacted the automotive point of sale, in particular EV purchasing (EV purchase likelihood). This also allowed us to test the point of sale from the perspective of different levels of market development, as Norway is quickly moving into early mass to mass EV markets, whereas the other four countries are at much earlier phases; considering that Denmark is the first country in which EV sales have recently slowed down significantly. Moreover, testing dealerships in different cities allowed us to assess the impact of the point of sale within different levels of urbanization and rural locations, such as northern towns of Trømso, Oulu and Akureyri.

We visited multi-brand and brand-specific, as well as EV-certified and non-EV-certified dealers. Out of the total sample, 42% were multi-brand and 58% were brand-specific dealers; 66% were EV-certified dealers. Interestingly, from our visits Finland and Denmark show a high percentage of EV-certified dealers within the visits conducted per country with ~75% and ~68% respectively, just after Norway (78%). Moreover, in the study we created we created two socio-economic profiles (Shopper), a PhD student (LN=0) and a business consultant, to test how other variables such as the availability of EVs for different segments, the sales approach and whether the attitude of the dealer changed based on higher budget expectations. Unexpectedly, the economic characteristics of the shopper profiles, such as budget, were not often involved in the sales conversation as salespeople would often base their assessment on ranking vehicle offerings by showing the lowest priced vehicle upwards, the driving patters (commuting or leisure), comfort (available space in the vehicle), and technological specifications, such as fuel efficiency, horse power, and technology packages (radio, air conditioning, etc.).

The gender and age of the dealers were recorded to determine if these variables influenced dealer assessments. Despite the fact that all the Nordic countries tested rank at the top of global English proficiency by non-native speakers, we considered language limitations. Language limitations were only reported in 8 visits, but were not considered as a barrier.

Variable	Description
Country	Denmark, Finland, Iceland, Norway and Sweden
City	Aalborg, Aarhus, Akureyri, Copenhagen, Gothenburg, Helsinki, Lund, Malmo, Oslo, Oulu, Reykejavik, Stockholm, Tampere, Trømso and Trondheim
Shopper	PhD student (LN=0) and business consultant
Gender of dealer	Male and Female
Age of dealer	0-100
EV brand availability	EV-certified and non-EV-certified
Brand specificity	Multi-brand and brand-specific
EV mentioned	EV brought up by dealer, EV omitted by dealer
Language	Records the times that language was a barrier in the provision of advice

Table 5. Recorded dealership variables. Shows the nine recorded variables after each dealership experience. Note: EV = Electric Vehicle. PhD = Doctor of Philosophy.

2.1.2.4 Expert Interviews

The primary data collection and analysis of the mystery shopping experiences was triangulated with 30 expert interviews with automotive manufacturers, importers, associations and other related organisations (see Appendix 6.7). These interviews are taken out of a pool of 227 expert interviews with more than 250 respondents to investigate the socio-technical barriers for electric mobility in the Nordic region, also conducted by the authors between 2016-2017. This larger interview pool follows a semi-structured approach, and therefore allowed for directly related topics, in this case car dealerships, salespersons and the automotive point of sale, to arise during the interview conversation. Based on this, we selected the interview answers used here. Interview duration was between 30 and 90 minutes, and interviews were fully transcribed and coded in NVIVO 11.

2.1.2.5 Data analysis

The data from audio files of each car dealership visit were transcribed and analysed. The notes and quotes recorded by the mystery shoppers were coded and evaluated based on a frequency analysis, (see Table 6). Moreover, dealership characteristics and the ranked answers to the designed questionnaire were analysed in three ways. Descriptive statistical analysis in Excel such as percentages, totals and averages were used to determine the overall status of the point of sale. Second, analysis of variance and single linear regressions were conducted to identify relationships between variables; and third, multilevel regression models were used to identify key determinants that influence EV purchase likelihood. Regression models included a one-way, two-way interaction variations as well as a tobit model following a backward elimination criteria that considers all variables (including dummification of categorical variables), and considering the Corrected Akaike's Information Criteria (AICC) as a measure of model fit when comparing alternative models(Burnham, Kenneth P; Anderson 2003). The ANOVA and regression models were conducted in SAS 9.4.

2.1.3 Results

First we highlight the data from our mystery shopping experiences coupled with complementary evidence from our expert interviews. Then we provide inter-country analysis based on ANOVA tests comparing salespeople's quality in selling, technological orientation, EV knowledge and the likeliness of customers purchasing an EV. This analysis highlights the impact of market conditions across the five investigated countries. Lastly, we use regression models to determine the factors that most influence the EV purchase likelihood.

2.1.3.1 Dealer disbelief and business barriers

Due to a perceived worse business case for EVs in comparison with petrol and diesel vehicles, dealerships and sales personnel pose a significant barrier for their uptake. Indeed, more than half of our expert interviews noted that both the car dealership and sales personnel lack a willingness to sell EVs because of anticipated low profitability, lack of knowledge and competence to sell, and extended sales time per EV purchase, in comparison with internal combustion engine vehicles (ICEVs).

Out of the total 126 dealership visits conducted, only 8.8% of the mystery shopping encounters resulted in the shoppers having preferred an EV option for their next car purchase over an ICEV; this drops to just 2.9% outside of Norway. More strikingly, in the 77% of the car dealerships visits that had EV brands and EV models available, the salesperson did not discuss the existence of their brand's EV. In Table 6 we present the most common barriers found by the mystery shoppers while conducting the visits (see Methods), with the top three being: salespersons at car dealerships dismissing EVs, misinforming shoppers on EVs attributes, and neglecting to mention EVs in the sales conversation.

Thus, a typical customer would have remained incognisant of the existence of EVs or misinformed about their performance. As an example, both dismissiveness of EVs and misinformation were evident in Visit 37 (V37), as a salesperson initially mentioned "*we don't have any [EVs]…they are more expensive, so they are probably not worth it*". But, when the shopper later pressed the topic of EVs, the salesperson acknowledged "*oh yeah, that's true, I do have a 100% electric [vehicle]*", though still completely disregarded it as a viable alternative.

Hence, customers that are not familiarised with electric vehicles would have likely remained incognisant about EVs as a purchasing option. This lack of salespersonnel's willingness to include the EV within the sales conversation was further corroborated with our interviews, where an expert from a leading EV brand manufacturer (R14) mentioned that only one out of ten of their dealers "*actually tried selling EVs last year*". R08 attributes this omission of EVs to the "*lack of willingness of the [salespersonnel] to actually promote [a] new technology*". Thus, a policy that requires OEMs to carry EVs within dealerships without the corresponding economic incentives would not necessarily result in more EV sales.

Barrier	Freq.	Example
Dismissive of EVs	28	*V86 – "the economics of fuel efficiency doesn't make sense",* which was a bit contradictory, because later the dealer said "*electricity was very cheap, so you would think that EV drivers would spend less on fuel [/power]*".
Misinforming the customer	24	*V22 –"we have this electric vehicle".* The dealer showed us an EV and said *"it only goes 80km".*
Neglecting to mention EVs	22	*V103* – Dealer said *"no we don't have this, you can only get this in petrol and diesel"* even though the shopper saw a brochure for EVs on the counter.
Depicting EVs as an inferior option	14	*V22 – "do not buy this [EV] it will ruin you, it will ruin you financially".*
Lack of EV availability and visibility	12	*V64* – The shopper saw a flyer for a Nissan Leaf, but the dealership did not have it in stock.
PHEVs and hybrids are not optimal for decarbonisation	12	*V111 – "most people just buy that because of the tax breaks and only use petrol and don't really use the electric part of it".*

Stating that the tax system favours conventional vehicles	11	*V24 – "if the diesel car is already tax free for 5 years, then means that it should be pretty environmentally friendly…[because] the government is quite strict for diesel and petrol engines, in terms of how much they pollute. So if these ones are below the limits of the government it must mean they are very environmentally friendly".*
Stating that the economics work against EVs	11	*V99 – "but I'm not sure if an EV would equate to financial savings, if you get more capital cost upfront with less tax would eventually mean less money overall. Because…you're giving the money now, but the savings are in the future, you don't know what's going to happen, what if you change car or in 10 years it's not really there".*
Lack of models for segments	10	*V124 – "if you do need the 4-wheel drive or interior space, go with the station wagon or SUV, not the EV".*

Table 6. Barriers to electric vehicles at car dealerships. The frequency of instances (N = 92 statements collected by the research team) in which salespersons made statements falling into one of nine categorical barriers, with examples.

In two-thirds of all shopping experiences, sales personnel strongly or solely oriented the customer to select a petrol or diesel vehicle, and actively dismissed EVs, even when dealerships had electric vehicle options for sale. For instance, in V82 the salesperson directed the shopper away from the full EV twice, with the dealer repeating "*no you should buy this car instead*". In directing customers away from EVs, we found several instances where dealers misinformed shoppers on EV specifications, such as range, tax benefits and charging experiences. For instance, in V70 the dealer said the range of the new E-golf was only 150km when the OEM advertises online a range of 300km in controlled conditions and 200km on regular driving (Volkswagen Denmark 2017). In V1, the salesperson told the shopper a 350km journey would take 2 days to complete because of charging times, but when asked for clarification later, admitted charging would add only about 2-4 hours.

Such misinformation is also tied to a low level of displayed knowledge by dealers: in 71% of the visits dealers demonstrated either low displayed knowledge or no knowledge at all. However, low knowledge of EVs may be related to the lack of training and educational programmes for salespersonnel. For instance, in our interviews R09 mentioned that some dealerships cannot sell EVs because corporate strategy targets EV training for only a portion of the dealerships where salespersonnel "*know nothing on charging infrastructure, nothing on the electricity or carbon emissions*". To this end, R13 noted that "*if you do not have the right tools or education [to sell EVs]…then you will try to sell the other car that you know by heart*".

The aforementioned barriers found in the mystery shopping visits potentially derive from currently unfavourable market conditions for full EVs in relation to ICEVs and even plug-in hybrids (PHEVs), as EVs are undoubtedly a more expensive option. As R18 mentioned, in countries like "*Sweden and Finland, the gap between these two technologies [EVs and ICEVs] is easily more than 10,000 euros*". In addition to the disparity in purchase price, although most countries have some moderate benefits for purchasing an EV (outside of Norway), incentives still more strongly favour ICEVs. For example, in V36, the dealer noted that "*the government likes petrol engines because there's not a lot of tax, [they are] very efficient, not a lot of emissions*", based on the fact that some petrol and diesel cars receive a tax exception for 5 years after purchase. Likewise, in V2, where EVs had a tax exemption, the dealer dismissed such benefits, noting that "*road tax is not really that high anyway*".

Perhaps unsurprisingly, salespeople tended to promote the vehicle that is easier to sell, which outside of Norway, was undoubtedly not an EV. Correspondingly, R15 noted that salespeople do not introduce EVs to the customer because "*it's more difficult to sell*". In addition to the price disparity between EVs and ICEVs, four of the interviewed OEM managers also noted the difficulty of selling, as EVs can take 2-4 times longer per customer compared to a typical ICEV. In this sense, our interviewees noted that "*there are much more questions*" (R16) before and post-sale and where sales personnel *"have to become consultants"* (R12) developing competences and new selling strategies, both of which detriments their willingness to promote EVs.

2.1.3.2 Geographic heterogeneity and country comparisons

Following each visit, the mystery shoppers ranked each visit on quality of salespersonship, technological orientation, knowledge, and purchase likelihood. In Figure 1 we show the least square means (LSMEAN) score of each country on these measures. When analysed at a geographic and regional scale, government policy and signalling seem to trickle downstream to the automotive retail level, which is evident when we consider the implications that different EV market conditions have on the point of sale within car dealerships.

The quality of salespersonship was relatively consistent across the countries, with Iceland (3.2) and Norway (4.0) recording the lowest and highest mean scores, respectively (Figure 1), suggesting that the disparity in market conditions between EVs and ICEVs affects the willingness of car dealerships and salespeople to sell electric vehicles. Quality of salespersonship was assessed based on the overall perceived ability, attitude, enthusiasm and professionalism of the salesperson while providing sales advice and attending to the shopper(Curry 1992). There was a statistically significant difference between Norway (LSMEAN=3.2) and the other Nordic countries (with the except of Finland) in the dealer's EV orientation (DK=1.51, t=5.70, p=<0.0001; IS=2.03, t=3.41, p=0.007; and SE=1.98, t=3.87, p=0.0016), which may reflect Norway's leadership in pro-EV incentives, and the less favourable EV market conditions in the other countries. Danish dealers oriented their customers most prominently towards ICEVs, perhaps reflecting the recent decision of the Danish government to tax EVs(Levering 2017). This political decision may have created the greatest disparity in the Nordic region between EV and ICEV conditions of the investigated countries, which is reflected in the difference between Denmark's ICEV (LSMEAN=4.7, t=-5.79, p=<0.0001) and EV (LSMEAN=1.5, t=5.70, p=<0.0001) orientation scores.

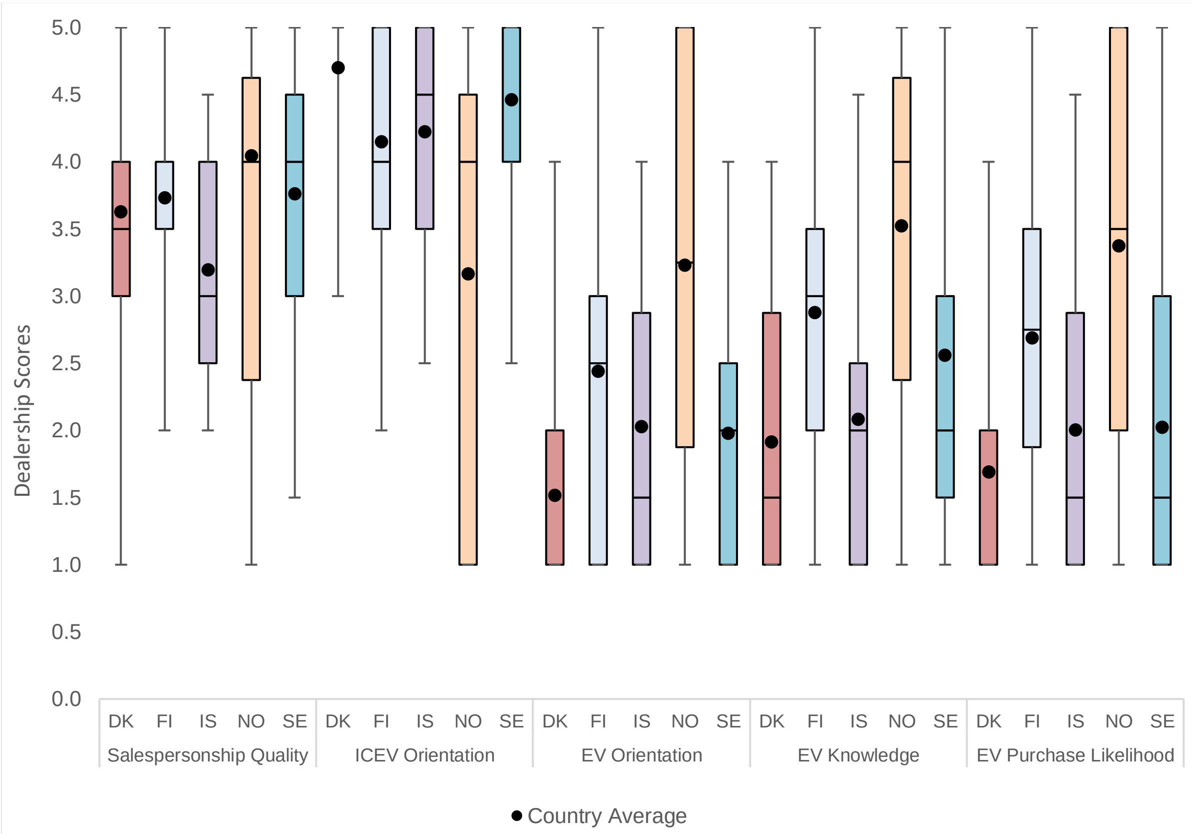

Figure 3. Salesperson rankings for electric vehicles in the Nordic region. Least square means scores for all five Nordic countries on quality of salespersonship, technology orientation, knowledge, and purchase likelihood, ranked on a Likert Scale from 1-5. The black dot shows the country average for a particular dealer ranking. The black line within boxes represents the median and the error bars show the minimum and maximum values. The box size emphasises the range of distribution between first and third quartiles, showing for example Norway' variation on EV Orientation with the highest general scores but also less EV-oriented dealers. Note: EV = electric vehicle. ICEV = internal combustion engine vehicle. DK = Denmark. FI = Finland. IS = Iceland. NO = Norway. SE = Sweden.

The level of EV knowledge was significantly different between the scores of Norway (LSMEAN=3.52) and Denmark (LSMEAN=1.91, t=5.27, p=<0.0001), Sweden (LSMEAN=2.56, t=2.93, p=0.032) and Iceland (LSMEAN=2.08, t=4.02, p=0.0009. Interestingly, Finland was not significantly different from Norway (t=1.95, p=0.29) on EV orientation (LSMEAN=2.43, t=2.43, p=0.113) and EV knowledge (LSMEAN=2.88, t=1.95, p=0.295), which may reflect the recent government commitment towards electrification, with a target of 250,000 vehicles by 2030 as well as the industry developed around EV ecosystems (Noel, Lance; Zarazua de Rubens, Gerardo; Kester, Johannes; Sovacool 2017). Perhaps as a result of recent changes to Danish vehicle incentives(Post 2017), Danish dealers oriented shoppers the least towards electric vehicles and showed the least displayed knowledge. This was evident in the many occasions where Danish dealers would recognise EVs but note that they were by far the least economic option compared to an ICEV. Notably, Denmark's orientation to petrol and diesel vehicles is so noticeable that its EV orientation (LSMEAN=1.51, t=3.07, p=0.021) and EV knowledge (LSMEAN=1.91, t=3.15 p=0.017) scores were significantly different than those for Finland (EV orientation=2.43, EV Knowledge=2.88), a country with fewer EVs in the national fleet, less developed charging infrastructure, and strong commitments to biofuel technology (Noel, Lance; Zarazua de Rubens, Gerardo; Kester, Johannes; Sovacool 2017). The disparity between the (strong) ICEV (LSMEAN=4.6, t=-4-59, p=0.0001) and (low) EV orientation (LSMEAN=1.98, t=3.78, p=0.0016) of Swedish dealers marks the second biggest difference between technological orientations, after Denmark, which may be explained by the taxation system that promotes company leasing EVs (as opposed to private leasing and ownership), and the apparent legacy of its automotive brands (Nykvist & Nilsson 2015).

Considering the results of Figure 3, it is unsurprising that Denmark ranks poorly compared to Norway and also Finland in terms of EV purchase likelihood. This finding corroborates the near non-existent sales figures of EVs in the country since the recent introduction of vehicle registration tax (European Automobile Manufacturers Association 2017; Levering 2017). Clearly, though, this does not mean EV technology is difficult to sell, given the improved likelihoods in Norway and even Finland, a country where EVs arguably may not fit the transportation demand as well as in Denmark. Despite Finland arguably has worse natural conditions for EV implementation than Denmark –colder weather, more scattered population settlements, less renewable energy supply and longer vehicle turnover cycles –the nation is still ranked second in the region in the likelihood of purchase (LSMEAN=2.7). These results suggest that policy mechanisms, government and industry signalling and promotion are evident downstream at the selling point and affect sales strategies and purchasing of electric vehicles.

2.1.3.3 Purchasing likelihood among adopters and demographic variables

Finally, we implemented a set of multiple regressions to model the factors influencing EV purchase likelihood at the point of sale, with the best fitting model shown in Table 7. This implies that a successful transition to EVs is most influenced by the EV orientation of the dealer to sell the vehicle and the displayed EV knowledge. The latter involves communicating the benefits of EV ownership which a neutral buyer may not be aware of. For example, in V112 the dealer mentioned "*insurance is 40% cheaper than comparable petrol or diesel*"; or in V21 where, despite not having EVs available to sell, the dealer spoke from their experience noting they "*didn't know they can drive that far…it wasn't that much of a problem to drive [from Gothenburg] all the way to Stockholm*". Moreover, whether EVs were mentioned is also influential. This refers to the fact that the dealer did not omit the EV, and recognised it within the sales conversation, regardless of whether it was the final vehicle option advised to the shopper.

Parameter	DF	Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.044117	0.117659	0.37	0.7084
EV orientation	1	0.820112	0.059037	13.89	<.0001
EV knowledge	1	0.128151	0.060371	2.12	0.0358
EV brand availability (EV Brand)	1	0.152927	0.108293	1.41	0.1605
EV mentioned (EV Said)	1	0.314911	0.163328	1.93	0.0562

Table 7. Regression Model Estimates. Parameter estimates of best fitting one-way interaction model. Note: EV = Electric Vehicle.

Other variables such as the gender of the dealer, the socio-economic profile of the EV shopper, the brand specificity of the dealership (if the dealership was multi-brand or brand-specific) and the location (country and city) were not significant determinants of the EV purchase likelihood.

Notably, there is no significant difference between the urban and more rural settings primarily located in the northern regions such as Akureyri (Iceland), Trømso (Norway) and Oulu (Finland). This contrasts with the idea that EVs are a better suited as a city car, and thus OEMs and car dealerships prioritise selling efforts on urban locations, as stated by R22. This was evident in Finland, as we found that a couple of major OEMs restricted full electric vehicle availability for sale to the greater metropolitan area of Helsinki. Thus, the dealerships visited in Tampere and Oulu could only suggest that a shopper travels 200-600 km to see or test drive a full EV model. Consequently, as the likelihood of EV purchase was not significantly different between these cities, suggesting that urban-based dealers were comparatively worse at promoting and selling EVs than rural-based dealers. This is unexpected given that urban-based dealers have the vehicles available, the infrastructure and certified expertise to sell EVs. This shows that the current intended strategy and promotion at the point of sale does not materialise into urban EV purchases.

The findings of the regression models suggest that car dealerships can increase the likelihood of EV purchase by having their salespersons actually include EVs in the sales conversation, noting the vehicle's attributes and actively mentioning EVs as an available option for purchase. As confirmed in our interviews, more robust training schemes that improve EV knowledge and sales confidence at dealerships, as well as operationalised EV sale processes that improve selling tools and delivery times of products, can encourage salespersons to promote EVs and increase the likelihood that EVs will be purchased.

2.1.4 Discussion Conclusion

Car dealerships and sales personnel serve as a major obstacle to the uptake of passenger EVs in the Nordic region, which mirrors industry and government favouritism towards conventional cars and lack of substantial or at least effective policies promoting EV diffusion. Indeed, policy and signalling from government and industry are evident at the point of sale, and in turn create deterrents for car dealerships and salespersons to promote and sell EVs. This is particularly evident as national market conditions create significant differences in the likelihood of purchasing EVs across countries, with Denmark—the only country to have introduced taxation on EVs—performing the worst among its Nordic neighbours. Despite market differences, our mystery shopping and expert interview data show that dealers were dismissive of electric vehicles, misinformed shoppers on vehicle specifications, omitted EVs from the sales conversation and strongly oriented customers towards ICEVs.

In turn, at an individual level, we found that orientation towards EVs and displayed knowledge by salespersons were the most important predictors of customer EV purchase likelihood, and ratings on these variables differed between countries. As Figure 4 reveals, our results suggest that an ordinary consumer would "very likely" or "likely" purchase an EV in less than 16% of the visits, and over one third of these are in one city, Oslo. When broken down further by city, the figures are even more striking—after Oslo and Gothenburg, our study's dealership experiences showed that an ordinary consumer has a 4% chance of adopting an EV, and in some cities—Malmo (Sweden), Lund (Sweden), Copenhagen (Denmark), and Aarhus (Denmark), the percentage is closest to 0. Thus, the likelihood of purchase increases when dealers at least included EVs in the sales conversation and informed the customer of (positive but also negative) EV attributes. This finding directly challenges the popular image that the Nordic region is successfully fostering innovation in electric mobility and diffusion of EV technology, outside of Oslo at least.

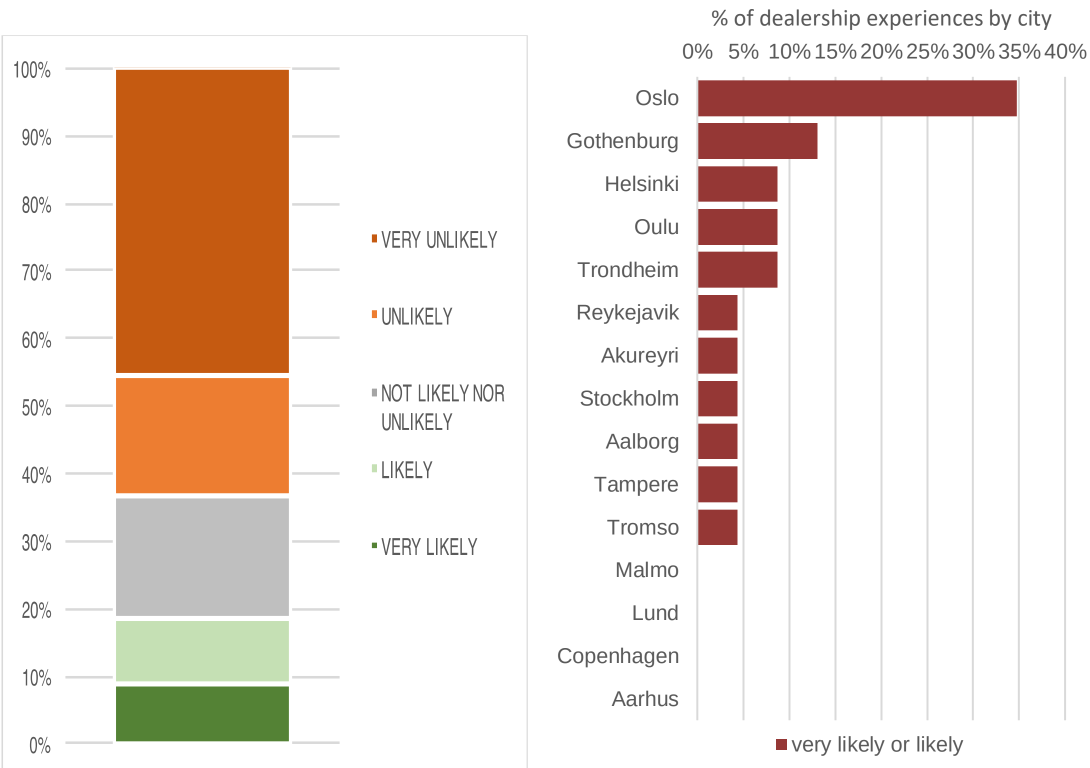

Figure 4. Likelihood of EV purchases. A) Percentage of dealership visits across entire Nordic region for each likelihood of EV purchase rating. B) Percentage of dealership visits that resulted in "very likely or likely" EV purchase ratings across each city..

Our study also reveals a compelling list of non-technical barriers that need to be overcome if EVs are to be diffused more substantially across the Nordic region, and perhaps elsewhere. Managers, industry experts and dealers believe the lack of willingness to promote and sell EVs derives from their low profitability, lack of EV models on site, lack of knowledge and competence about EV specifications, and that EVs take longer to sell. Given these factors, salespeople opt for the known and easier-to-sell conventional cars. Moreover, EVs were seen to negatively affect dealer profitability, not only from an initial investment perspective (setting up charging infrastructure and additional personnel training), but also due to a decreased need for maintenance and other services and consequent reductions in dealer revenue. These barriers resemble those in North America, in particular the lack of availability of EV models, longer lead times and willingness from salespersons to sell the technology(Cahill et al. 2014; Reports 2014; Matthews et al. 2017).

To this end, we find that policy and business strategy should be developed to amend the barriers at the point of sale and support EV uptake, particularly considering that EVs could accelerate both the decarbonisation of the transport and electricity sectors. First, policy intervention is necessary to reduce the net gap between the purchase price of EVs and ICEVs, as without price parity, dealers have little to no incentives to sell more expensive EVs to neutral shoppers. Moreover, policymakers should recognise both the actors and dynamics at the automotive point of sale; for instance, by developing tax systems that explicitly address capital costs of EVs instead of to costs of ownership. Furthermore, at an industry and business level, training schemes for dealers and educational programmes for customers can significantly improve sales techniques, knowledge, and confidence in EV technology. This can help operationalise sales processes and reduce the time spent per EV sale. Finally, government should encourage car dealerships, through a potential standard or reward scheme, to revise sales commission and compensation structures to increase the willingness of dealerships and salespersons to engage with EV technology. At the city level, planners in Malmo, Lund, Copenhagen, and Aarhus in particular must recognise that our study experienced ~0% likelihood that consumers would decide to purchase vehicles at dealerships within their territory. Planners in Oslo, by contrast, have certainly cultivated a strong, comparatively supportive environment for EVs. Future research should consider local and national policies when analysing dealership motives and influence on the diffusion of EVs.

Ultimately, the implication seems to be that EVs are at a severe disadvantage at the point of sale when competing with petrol and diesel options. Without more progressive action on behalf of industry and government, dealers have little to no incentive to properly sell EVs, even in a Nordic region so steadfastly committed to decarbonising transport.

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2.2 Who will buy electric vehicles after early adopters? Using machine learning to identify electric vehicle mainstream buyers and their characteristics.

The second research article introduce in this dissertation focuses on exploring the consumer level of the automotive market, in particular the prospective mainstream market of EVs. It considers that most current EV markets remain in nascent stages, with buyers being categorised as early adopters or pioneers. However, if electric vehicles are to successfully contribute to the decarbonisation of transportation, they must reach mainstream consumer segments. To investigate the underlying causes of EV interest and to determine the potential next wave of EV buyers, this study draws data from an original dataset (n = 5067) across the five Nordic countries of Denmark, Finland, Iceland, Norway and Sweden. A machine learning model, based on the k-means method, is used for the analysis, creating six consumer segments around prospective EV adoption. The study finds that three consumer clusters account for 68% of the (sampled) population, are primed for EV adoption and represent the near-term mainstream EV market. The findings corroborate that price is a main determinant in reaching these mainstream consumers, while suggesting that vehicle-to-grid can contribute to the attractiveness of EVs and their uptake. The study corroborates and stresses the importance that policy and industry decision-makers must create an equally competitive market place for EVs and develop strategies and policy that consider the characterises and interests of mainstream EV customers.

2.2.1 Introduction

Electric vehicles (EV) coupled with a low carbon power supply have the potential to dramatically reduce transport emissions and contribute further to the decarbonisation of society (Kennedy et al. 2014; Needell et al. 2016; Richardson 2013; Muneer et al. 2015; Noel et al. 2017). This potential for decarbonisation is recognised globally where by 2016, fourteen countries had set national EV deployment targets between 2020 and 2030 (International Energy Agency 2017) with China aiming for 35 million by 2025 (Reuters 2017). National efforts for decarbonisation of transport and support of EV technology have been further evidenced with Norway, France, the United Kingdom and India banning petrol and diesel vehicle sales as early as 2030, with China expected to follow in the near future (Petroff 2017; BBC 2017). At industry level, most automotive manufacturers have launched at least one BEV or PHEV model, with some traditional brands even indicating their production will only include EV models by the end of this decade (The Guardian 2017). At a retail level, the automotive market continues to see increases in the share of EV sales across many countries, with Norway still leading the way where 1 in 3 vehicles is fully electric (Eafo 2017). However, EVs have historically had unmet high expectations around Battery Electric Vehicle (BEV) and Plug-in Hybrid Electric Vehicle (PHEV) technology (Melton et al. 2016) and, in spite of the progress above mentioned, EVs accounted for only 0.2% of the total global passenger vehicle fleet in 2016 (International Energy Agency 2017), and have yet to succeed in displacing petrol- and diesel-based passenger vehicles.

Many have explored the challenges and barriers electric vehicle face for wide-scale implementation (Nilsson & Nykvist 2016; Berkeley et al. 2017; Tran et al. 2012). From the technical elements such as battery capacity and range (Kempton 2016; Bonges & Lusk 2016; Dimitropoulos et al. 2013; Pearre et al. 2011a), to price and their economic comparison against internal combustion engine vehicles (ICEV) (Falcão et al. 2017; Lévay et al. 2017; Ito & Managi 2015; Hagman et al. 2016); while, a plethora of studies have increasingly investigated EVs in relation with the power system (Richardson 2013; Poghosyan et al. 2015; Mwasilu et al. 2014; Lund & Kempton 2008; Gnann et al. 2018; Kempton & Tomić 2005a), as well as the optimal configuration for the EV ecosystem; particularly its recharging network (Brooker & Qin 2015). Furthermore, it has been noted that the proliferation of EVs is currently deterred from the lack of availability of models for specific car segments, where EVs have not been able to compete at retail level with the well-established ICEV market (Berkeley et al. 2017). Such established automotive regime, led by the legacy of Original Equipment Manufacturers (OEMs), has also contributed to the development of social norms around cars, their essence and use, which represents a strong barrier for electric vehicles (Nykvist & Nilsson 2015). Recent research has also pointed at retail bottle necks across the automotive supply chain linking government and industry messaging to sales strategies by automotive dealerships (Zarazua de Rubens et al. 2018). Other literature has explored the social, political and market aspects of EVs, from taxation and policy incentives (Mersky et al. 2016; Bakker & Jacob Trip 2013; Harrison & Thiel 2017), to the consumer-focused studies that investigate the user related challenges, linked to charging infrastructure(Sun et al. 2017) such as range anxiety (BROAD 2016; Noel, Zarazua de Rubens, Sovacool, et al. 2018). Here the body of literature that explores the consumer acceptance of EVs and the determinants of purchase is large, with studies focusing on the profiles of EV owners and drivers behind EV purchases, such pro-environmental attributes (Vassileva & Campillo 2017; Egbue & Long 2012; Rezvani et al. 2015; Kim et al. 2018).

Studies on consumer adoption of technologies have followed, and criticised, the popular framework of diffusion of innovations (Rogers 2003), which categorises consumers into stages of adoption: innovators, early adopters, early majority, late majority and laggards (Rogers 2003; Axsen et al. 2016; Lieven et al. 2011). Specifically, for electric vehicles, studies have focused on the initial stages of innovation to identify the characteristics of early adopters and understand potential purchasing behaviours to foster EV deployment. Practically irrespective of geography, literature has identified early adopters of EVs as individuals of middle to high income and age, typically males, with graduate or postgraduate degrees, that can be technologically and environmentally inclined, as found in Austria (Wolf & Seebauer 2014), Canada (Axsen et al. 2016), Germany (Lieven et al. 2011; Plotz et al. 2014), Norway (Mckinsey & Company 2014), United Kingdom (Campbell et al. 2012), United States (Hardman et al. 2016; Carley et al. 2016) and Sweden (Vassileva & Campillo 2017). Others have gone beyond and added further granularity in exploring early adopters by identifying them as high-end and low-end (early) EV adopters with differences in income and levels of education (Hardman et al. 2016). This, arguably, reflects the existing EV market with higher end products available like Tesla models and others from more traditional brands such as Volkswagen E-UP! or Nissan Leaf. Table 8 presents a summary of the main literature around EV adoption, focusing on studies with empirical data sets, that looked into the characteristics and profile of electric vehicle adopters.

Author(s)	Sample Size	Sample Attributes	Country/Region	Early Adopters profile
Axsen et al. (2016)	1848	94 EV owners and 1754 new vehicle buyers	Canada	High income, high education, male, middle aged, home owners.
Campbell (2014) and Campbell et al. (2012)	413	General Public	United Kingdom	High income, high education, multi-car households.
Hardman et al. (2016)	340	EV owners	North America	Middle aged, male, high education, high income, multi-car households. Differentiation between high-end and low-end adopters.
Carley et al. (2013)	2302	General Public	United States	High income, high education, environmentally sensitive.
Hidrue et al. (2011)	3029	General Public	United States	Young to middle aged, high income and high education.
Peters and Dütschke (2014)	969	92 EV users in sample of 969 EV interested people	United States	Middle aged, male, multi-car households, higher willingness to pay for car (EV).
Plotz et al. (2014)	210	General public with high interest in EV	Germany	Middle aged, above average income, males, technical professions, multi car households.
Vassileva and Campillo (2017)	247	EV owners	Sweden	High income, high education, male, middle aged.

Table 8. Summary of main EV adoption studies. Notes: Constructed by Author.

Despite this depth and range of research, EV adoption studies have focused primarily on identifying current EV owners and buyers, their characteristics, interests and vehicle preferences. However, by definition early adopters (13.5%) (Rogers 2003) represent a minority of the market, and currently even the global EV leader, Norway, only totals around 5-6% of EVs on its national passenger car fleet (Norway 2018). Therefore, research must be focused on identifying the dynamics and characteristics of the early to late majority automotive consumers to continue to push the transition to electric vehicles; particularly, if countries expect to use EVs to meet transportation decarbonisation targets.

To the authors knowledge, one exception exists of a British Columbia-focused (Canada) study that goes beyond exclusively looking into early adopters and offers insights into potential early and late EV adopters (Axsen et al. 2016). In this way, the study highlights that early and late majority consumers are relatively similar to each other, as compared with early adopters: for example, being less environmentally inclined or having lower earning incomes. Notably its shown that non-early adopters have relative low EV knowledge and are more likely to prefer a plug-in hybrid vehicle (PHEV) as opposed to a full-electric. However, while the study offers insight into the potential mainstream EV automotive market, it does not offer further granularity and identify specific consumer groups, their characteristics, preferences and how these fit within EV adoption; as well as being limited to a single region within a particular country. In consequence, research is needed to categorically identified different types of consumer segments and how these fit within potential EV adoption international markets. This with the purpose of develop an understanding of such consumers, their relation to EVs and potential for adoption, in order to create policy and strategies to reach the mainstream market.

For this reason, this paper investigates the potential mainstream market for electric vehicles, focusing on mass-market consumers. It uses a machine learning method, k-means, to provide unique insight into demographic and socio-economic characteristics, vehicle and mobility preferences, and electric vehicle and vehicle-to-grid interests across five countries in the Nordic region (Denmark, Finland, Iceland, Norway and Sweden). Using an original data set of over 5,000 survey respondents, the model creates six customer clusters and analyses the potential for electric vehicle adoption of mainstream consumers. In addition, the uniqueness of the analysis is also substantiated by the inclusion of five distinct markets, with different tax, regulatory, commercial and social conditions on each country, as well as different stages of EV penetration. For example, from the EV global leader Norway, to recent intermediate adopters in Sweden and Finland, and other less developed EV markets of Denmark and Finland. The study presents below the methodology, description of data and assumptions used to create the analysis of the study. It then moves to present and analyse the results based on the identified customer clusters and their relationship to EV adoption.

2.2.2 Methods

2.2.2.1 Data collection

The primary method for data collection is a survey, that consists of 44 total questions divided into four parts (see Appendix 6.5): 1) Vehicle History & Background, 2) Vehicle Preferences, 3) Electric Vehicle Choice Experiment, and 4) Demographics. The choice experiment is not reported on this paper. The first survey section includes questions about the respondent's vehicle background and the current mobility patterns, for example: driving patterns and prospective vehicle ownership. The second section included questions about vehicle and mobility preferences such as acceleration in a vehicle, or size and safety. This section also included questions about electric vehicles, particularly regarding attributes such as the importance of driving range, battery life and price. These features were answered in a five-point Likert scale ranging from very unimportant/uninterested to very important/interested. The last section of the survey included questions of demographic information and attitudinal questions on the environment.

The distribution of the survey was online and anonymous, available from September 2016 to November 2017. Prior to its launch, the survey was piloted with local populations and with several survey-design and topic-matter experts. Through this process, the survey made several improvements to its design, structure, and language. The survey was distributed both in a randomised sample and a non-random sample. The random sample was collected by the survey consulting firm Qualtrics across the five countries, with the aim to be representative of the Nordic populations primarily in age, country and gender with a lower boundary that respondents had to be over the age of 18 years old. In total the random sample includes 4,602 completed responses with a nearly evenly distributed across the four countries (due to the difficulty of reaching respondents Iceland has slightly less respondents). Moreover, the survey also included 1,292 non-random completed responses. Together, both sample totalled 5,894 responses. Notably, many completed surveys were only partially filled in, particularly within the non-randomised sample and were therefore not considered in the analysis. This puts the total respondent number at 5,067, as shown in Table 9.

Country	Respondents (random)	Respondents (non-random)	Total
Denmark	953	185	1138
Finland	962	143	1105
Iceland	496	214	710
Norway	959	103	1062
Sweden	952	100	1052
Total	4322	745	5067

Table 9. Survey distribution by sample and country.

2.2.2.2 Model analysis

The survey was analysed using an unsupervised learning algorithm from machine learning called k-means clustering, which clusters data based on its similarity. Machine learning is a subfield of computer science and it can be categorised as an artificial intelligence method, which models data-relations even if the representation seems impossible (Voyant et al. 2017). The method of k-means clustering involves vector quantization and aims for data-partition in (n) number of observations into (k) clusters. K-means is an unsupervised method meaning there is no particular outcome to be predicted, rather the algorithm tries to find patterns of data to be evaluated. Each observation of the data set is randomly assigned to a cluster and the algorithm finds the cluster's centre. This is then iterated by 1) reassigning data points to the closest cluster and 2) calculating the new centroid. These steps are reproduced until the variation within a cluster cannot be reduced. The method works with Euclidian distances between data points and cluster centroids. Its equation can be summarised in Equation 1, where "S is a k cluster partition represented by vectors y_i *(i* $\in$*I)* in the M-dimensional feature space, consisting of non-empty non-overlapping clusters S_k, each with a centroid C_k *(k=1,2,…K)"* (Kodinariya & Makwana 2013, p.91).

$$W(S,C) = \sum_{k=1}^{K} \sum_{i \in S_k} \parallel y_1 - C_k \parallel^2$$

Equation 1. K-means equation. Note: Obtained from Kodinariya & Makwana (2013).

The analysis was conducted using Rstudio Version 1.1.442. The data processing (cleaning) involved converting variables into the right classes (numeric), creating dummy variables for specific categorical variables and imputing specific observations. The selection of the clusters had a two-fold rationale. On one hand, a quantitative approach was followed to determine the number of k clusters to model, the elbow-method, as it is the most common and oldest method for determining the optimal number of clusters within a set (Kodinariya & Makwana 2013). This method resulted in six clusters as the optimal number. To validate cluster-selection applied to the topic at hand, electric vehicle adoption or diffusion, cluster selection was cross-referenced with qualitative analysis by comparing consumer groups against the theory of diffusion of innovations (Rogers 2003). As noted above, the stages of adoption are categorised in five waves of consumers, however, this categorisation does not include a category for non-adopters. Referring to consumers that will not adopt the technology, in this case EVs. Thus, a sixth group is included for the likely non-adopters. Therefore, the model was then run with six k clusters, using a parameter of 300 iterations to find the optimal centroids.

2.2.3. Results

The analysis created six customer clusters based on demographic and socio-economic characteristics, mobility and vehicle preferences, and stated electric vehicle and vehicle-to-grid interests. After analysis, these clusters have been labelled: *Petrol Heads* (Cluster 1), *Blue-collar Moderates* (Cluster 2), *Status Seekers* (Cluster 3), *Public Mobiles* (Cluster 4), *Sceptics* (Cluster 5) and *Greens* (Cluster 6). We find that particularly clusters (2) *Blue-collar Moderates* and (6) *Greens* are the potential mainstream EV adopters, consisting of 48% of our total sample and representing the potential mass market entry-point to target for EV as other have referred to this group as early adopters (Wolf & Seebauer 2014; Vassileva & Campillo 2017; Axsen et al. 2016; Neubauer et al. 2012; Plotz et al. 2014). This consumer group remains the most immediate to target considering that they own 70% of all EVs in our data set and have a 28% overall EV adoption rate. Cluster 4, Public Mobiles, in this case it is considered as a fourth cluster to target but it is not considered as near-term prospect for EV adoption, while the remaining clusters (1) Petrol Heads and (5) Sceptics will be the last to adopt EVs based on the below results.

2.2.3.1 Demographics and context

Table 10 summarises the demographic and context data from each of the EV adoption clusters across the entire Nordic region. The differences between clusters and characteristics are all significant at 95% confidence level. Early EV adopters, below categorised as Status Seekers, resemble the characteristics found in the literature of educated middle to high income and age individuals, typically males, with graduate or postgraduate degrees. In our sample this group has the highest annual income with the most number of respondents (18%) earning above 90,000 euros/year. Status Seekers also show the largest gender gap of the group with 70% of the cluster's respondents being male and the second oldest mean age (43 years old). The cluster also has 60% of the individuals as postgraduates with predominantly liberal political views (33%), followed by social democrats (20%). Despite Status Seekers did not rank environmental importance as high as other clusters (third highest), in reality this group shows the most investments in both solar PV and home energy efficiency measures, as well as ranking second highest among clusters in stated environmental behaviour by increasing recycling and reducing water consumption. Arguably such behaviour is more related more to the cost-signalling of new technologies rather than the environmental appeal (Noel, Sovacool, et al. 2018).

Greens (cluster 6), is the group with the second highest annual mean household income (~€50-70k). In contrast to Status Seekers, the Greens cluster shows the second largest gender gap with 60% of respondents being female and shows the lowest mean age across all clusters (40 years old). This group has the second highest percentage of postgraduate educated individuals (50%), with 36% stating a Socialist Green political orientation. It is then not surprising that this cluster both values environmental importance the most and shows the highest stated environmental behaviour, having changed their diet, decreased water consumption and increased recycling efforts. The group however, ranks third on having invested in solar PV, which can derive from lower stated household income and a lower inclination for interests in new technologies as discussed in later sections.

To some extent similar, the Blue-collar Moderates cluster is just below Greens on annual household income, percentage of students (22%) and mean cluster age (40.9). However, this cluster is not driven by an environmental lifestyle as these individuals ranked environmental importance the second lowest among all clusters, are the least likely to have invested in solar PV and second least likely to have decreased water consumption; which is arguably attributed to the lower stated household income (4th among clusters). Gender-wise, this cluster is more evenly spread with 53% of male individuals and 46% female.

The Public Mobiles cluster has a female majority (60%) and the second lowest annual mean income, with 29% of the cluster's individuals stating €10-30k household income a year. It has the largest percentages of retiree's (19%) and unemployed (16%), with the third oldest mean age (41.6 y/o). The group has the second highest stated environmental importance across all clusters, however, in practice, Public Mobiles are the least likely to have invested in solar PV or energy efficiency measures, though this may be a result of the lower stated income. Nonetheless, they also are ranked comparatively lower (2nd and 3rd lowest) on stated environmental behaviour, implying a lack of pro-environmental action. This group has the largest percentage of urban settlers.

Finally, the last two clusters Sceptics and Petrol Heads (no.1) relate to each other on the lack of environmental lifestyle ranking it as the lowest and second lowest among all clusters. However, the former cluster has the third most urban settles, whereas the latter has the second most rural. Age-wise, Petrol Heads has the highest mean age (45.5 y/o) with the most individuals over 55 years old, whereas Sceptics are ranked third oldest age (41.5 y/o). Educationally, the latter group has the least completed degrees among all clusters.

Demographics and context	**Cluster 1** Petrol Heads	**Cluster 2** Blue-collar Moderates	**Cluster 3** Status seekers	**Cluster 4** Public mobiles	**Cluster 5** Sceptics	**Cluster 6** Greens
Custer size (n = 5067)	12%	26%	20%	14%	6%	23%
Gender***						
Male	55%	53%	70%	37%	39%	39%
Female	44%	46%	29%	60%	55%	60%
Other	0%	1%	0%	1%	3%	1%
Age (respondent)***						
15-34	29%	42%	30%	42%	39%	43%
35-44	18%	16%	25%	17%	17%	21%

45-54	22%	18%	23%	16%	19%	16%
55-65	18%	14%	14%	16%	15%	12%
>65	13%	10%	8%	10%	10%	8%
Household income (pre-tax)***						
0-10k	7%	9%	2%	15%	12%	9%
10-30k	22%	25%	9%	29%	22%	24%
30-50k	26%	23%	22%	18%	13%	26%
50-70k	14%	12%	27%	8%	11%	14%
70-90k	8%	5%	17%	3%	4%	8%
>90k	5%	2%	18%	2%	4%	5%
Occupation***						
Other	3%	4%	1%	3%	4%	4%
Unemployed	6%	9%	2%	16%	13%	9%
Retired	18%	15%	8%	19%	14%	14%
Student	11%	22%	4%	21%	9%	23%
Academic Institution	8%	0%	0%	2%	3%	0%
NGO	6%	4%	6%	4%	6%	6%
Government	8%	9%	17%	9%	9%	12%
Private sector	34%	29%	60%	19%	24%	28%
Education (completed)***						
Prefer not to say	14%	17%	5%	17%	30%	8%
Other	6%	4%	3%	5%	4%	5%
Secondary (high-school)	16%	26%	8%	21%	18%	11%
Undergraduate	27%	28%	21%	25%	17%	26%
Postgraduate	37%	25%	63%	31%	31%	50%
Living Area***						
Rural	23%	18%	24%	17%	13%	17%
Sub-urban	47%	48%	48%	40%	48%	42%
Urban	29%	34%	28%	43%	39%	41%
Political Orientation***						
Prefer not to say	29%	39%	14%	31%	43%	17%
Other	8%	8%	4%	7%	10%	7%
Conservative	13%	10%	16%	7%	9%	5%
Socialist Green	9%	6%	12%	26%	12%	36%
Social Democrat	20%	21%	20%	15%	15%	21%
Liberal	21%	17%	33%	14%	12%	15%
Environmental Importance***						

Unimportant or very unimportant	11%	7%	3%	4%	20%	0%
Not important nor unimportant	42%	39%	21%	23%	42%	7%
Important or very important	47%	54%	76%	73%	38%	92%
Environmental behaviour***						
Installed energy efficiency	33%	27%	73%	28%	26%	42%
Invested in Solar PV	5%	3%	31%	5%	14%	7%
Changed Diet	31%	36%	51%	53%	32%	72%
Decreased Water Consumption	38%	32%	51%	37%	30%	53%

Table 10. Comparing clusters demographics and context. Note: Data source is Nordic Vehicle Preferences Survey 2016-2017. ***Differences indicated between clusters and variable samples using chi-squared analysis at 95% confidence interval.

2.2.3.2 Mobility and vehicle interest

In Table 11, the results for mobility and vehicle preferences are summarised for the six cluster groups. Vehicle ownership is led by the Status Seekers and Petrol Heads clusters with 97% and 88% of ownership and a vehicle ratio of 1.81 and 1.42 cars per household. Next, the Blue-collar Moderates cluster with 81% and 1.23 and (Greens with 71% and 1.00 vehicles per household. The last two groups, Sceptics and Public Mobiles, show <50% ownership and less than 1 car per household. These ownership rates, however, arguably are expected to change in the next five years, as it may be that the Blue-collar Moderates and Greens will join the Status Seekers with over 50% of respondents stating the likeliness of purchasing their next vehicle within the next 5 years. Expectedly, Public Mobiles and Sceptics stated less purchasing likelihood.

In terms of expected money spend on the next vehicle purchase, our analysis shows that the majority of respondents are considering a vehicle of €30,000 or below, with only the Status Seekers having more than 20% or more of respondents expecting to spend more than €30k on their next vehicle. Clearly, for this cluster, the price of an EV poses less of a barrier and may explain the group interested in making substantial investments in EVs like Tesla. The Greens have the second largest expected spend with 25% their respondents willing to spend between €20k to €30k, followed by the Blue-collar Moderates (21%). However, this puts them just under the average price of so-called "average" EVs like a Nissan Leaf (which average price in the Nordics in the mid €30k price range). Consequently, these results show a potential market cut-off point for mass penetration of electric vehicles, that is, EVs should be placed at least within the €20-€30,000 bands in order to be adopted by mainstream consumers.

The Petrol Heads and Status Seekers clusters show the most kilometres driven per day, with 19% and 34% of their respondents stating to drive more than 50 km a day. On the other hand, while stating high vehicle ownership rates and short term purchasing intentions (even above the Petrol Heads), the Blue-collar Moderates and Greens clusters have their majority of respondents driving 20km a day or less. Moreover, 34% of the Greens reports that they do not drive, which may be attributed to their pro-environmental preferences of other modes of transportation. Notably, only the Status Seekers have more than 10% of respondents that stated they drive 80 km or more a day, meaning that in all other clusters at least 90% of respondents (and 83% of Status Seekers) daily driving requirements could be met with an EV even in harsh winter conditions.

Mobility & Vehicle Interest	**Cluster 1** Petrol Heads	**Cluster 2** Blue-collar Moderates	**Cluster 3** Status Seekers	**Cluster 4** Public mobiles	**Cluster 5** Sceptics	**Cluster 6** Greens
Vehicle ownership***	88%	81%	97%	39%	48%	71%
Vehicles (cars) per household***	1.42	1.23	1.81	0.68	0.91	1.00
When are you buying your next car***						
Not sure don't know	22%	16%	4%	97%	66%	16%
Don't expect to buy one	2%	2%	1%	3%	3%	3%
Within next year	16%	13%	23%	0%	4%	12%
1-5 years	47%	54%	60%	0%	18%	51%
5-10 years	12%	13%	11%	0%	7%	16%
>10 years	1%	2%	2%	0%	2%	1%
How much are you expecting to spend***						
Not expected to buy	8%	3%	1%	98%	55%	4%
€0-10k	25%	27%	7%	2%	15%	22%
€10-20k	33%	37%	20%	0%	13%	39%
€20-30k	16%	21%	28%	0%	10%	25%
€30-40k	9%	8%	21%	0%	2%	7%
€40-50k	5%	3%	11%	0%	1%	3%
>€50k	3%	2%	12%	0%	4%	1%
KMs driven per day***						
I don't drive	17%	23%	4%	69%	53%	34%
0-20km	33%	37%	20%	19%	17%	39%
20-50km	31%	29%	41%	8%	16%	21%
50-80km	10%	6%	17%	2%	8%	4%
80-100km	3%	2%	8%	1%	3%	1%
>100km	5%	2%	9%	1%	2%	1%
Drivers licence***						
I don't have one	7%	10%	1%	34%	40%	12%

Less than a year	2%	4%	4%	3%	2%	3%
1 to 5 years	10%	15%	11%	9%	9%	13%
5-10 years	9%	12%	10%	10%	5%	11%
>10 years	73%	60%	75%	44%	44%	60%

Table 11. Mobility and vehicle interests. Note: Data source is Nordic Vehicle Preferences Survey 2016-2017. ***Differences indicated between clusters and variable samples using chi-squared analysis at 95% confidence interval.

Figure 5 shows the results of each cluster ranking importance of eight vehicle characteristics when thinking on their next vehicle purchase. Here it is found that Status Seekers are mostly driven by aesthetics and speed performance of a vehicle as well as the comfort and size implying interest in larger sports vehicles, noting that price is the least ranked attribute. These preferences are similar to the Petrol Heads, who are also attracted to speed and acceleration attributes of a vehicle and its comfort and size. Expectedly, this cluster has the least interest in fuel economy and on ease of operation. Thus, for both of these groups, the technical performance of the EV, particularly the potential to out-accelerate ICEVs, may be an important selling point.

The Blue-collar Moderates cluster is the second most sensitive to the capital cost of vehicles, as well as second most interested in size and comfort. However, they also show place moderate importance on fuel economy (3rd amongst clusters). Similar to Blue-collar Moderates, the Public Mobiles cluster is mostly interested in price (first among clusters) followed by in safety of vehicles, and fuel economy. Obviously, because Public Mobiles are unlikely to purchase vehicles, they would be least willing to pay for a product that they do not want. The group shows the least interest in speed and acceleration, size and comfort, and design and style attributes of vehicles.

On the opposite spectrum, the Greens have a distinct interest for fuel economy, technical reliability, safety and ease of operation. They are the fourth least interested on speed and acceleration, and design and style. Lastly, the Non-environmental show a distinctive stated disinterest on the attributes which can be in part tied to the reported inability to legally drive and therefore redundancy in buying a car, since 40% of the cluster’s respondents state to not have a driver’s licence.

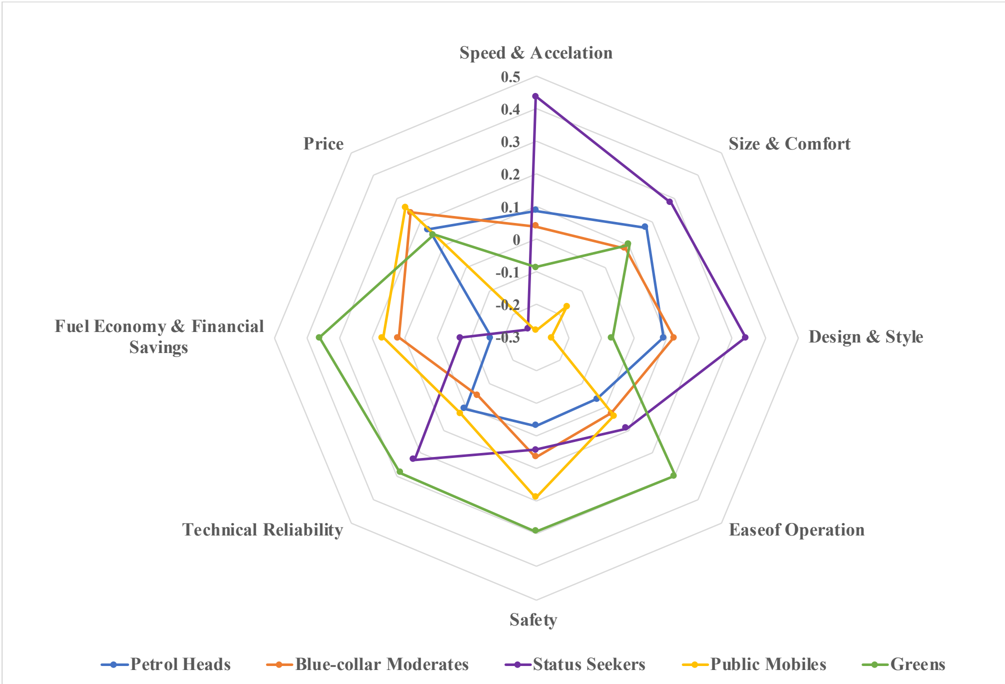

Figure 5. EV adoption clusters general vehicle preferences. Note: Constructed by author. The figure does not include Cluster 5 (Sceptics), since this group sows a complete disinterest in all attributed (ranked at -2.5) which distorted the visuals of the figure.

2.2.3.3 EV and V2G interest

The Status Seekers cluster resembles the characteristics of what others have called early EV adopters, and on this study this group accounts for 70% of all EVs across the recorded sample, followed by the Blue-collar Moderates cluster with 16%. For electric vehicles, Figure 6 shows the results of EV interest compared against real EV ownership where remarkably the Greens cluster shows the most EV interest, being mostly attracted to government incentives and environmental profile, but the second least ownership ratio with only 1% of respondents having EVs. This can be explained as the cluster has most respondents (86%) with a stated purchasing budget of below €30,000 which is below most EV-available models of the previous 5 years. In turn, this reinforces the Norwegian success on EV adoption, and continues to stress the importance of government incentives considering that, through policy, the country placed EVs commercially below the €30,000 boundary.

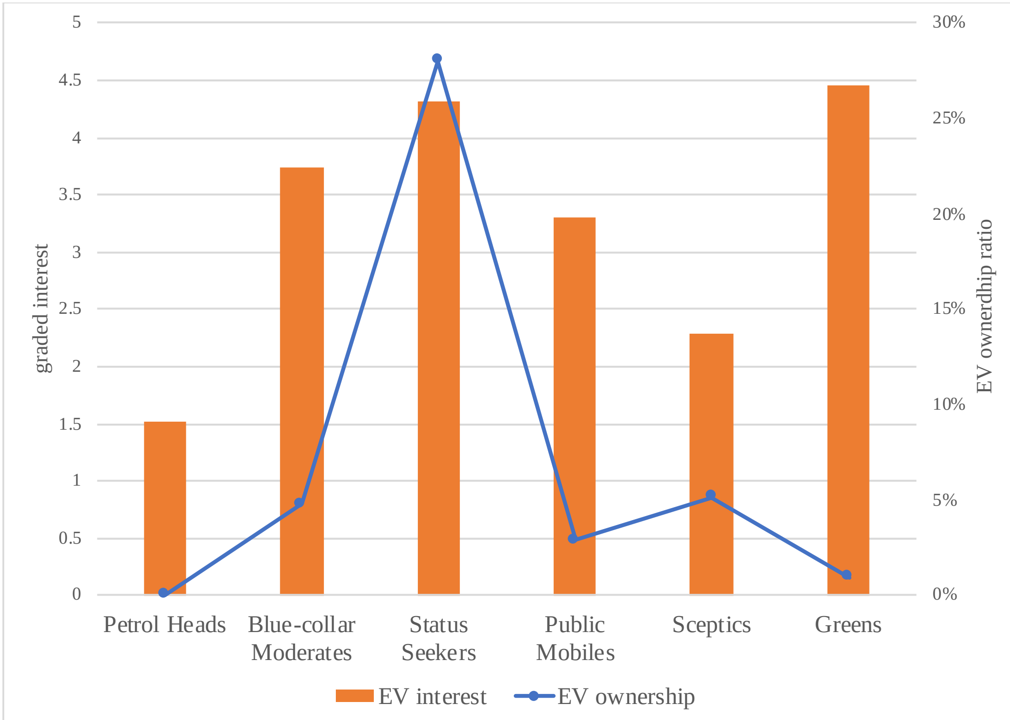

Figure 6. EV Interest vs. EV Ownership. Note: Constructed by Author.

The Blue-collar Moderates cluster comes with both the third highest EV interest and ownership rate as this group is mostly interested on the financial savings as the low cost of operation, as well as the EV as a new technology. These can relate to the socio-economic profile of the cluster having the second youngest respondents interested in new-technologies but also their price-sensitivity, as shown in Figure 1 above. The Public Mobiles cluster shows a relatively high EV interest (4th highest) which is mainly attributed to their stated pro-environmental behaviour and is corroborated as they rank the environmental attributes of EVs, as the second highest among clusters. On the opposite scale, Petrol Heads is the only cluster with a reported zero percent EV ownership, as well as having the least EV interests across groups. Their stated disinterest primarily focuses on lack of public infrastructure, battery charging times and the cost of ownership (capital) of EVs. Considering this group shows the current second most vehicle ownership ratio, with all owned vehicles being petrol or diesel, and the least EV interest, it might result the most difficult group to transition into electric mobility.

In terms of characteristics specific to EVs, Figure 3 shows the vehicle profile as ranked by each cluster. Most evident is the stated environmental importance of EVs, where the Greens score this element with the most importance and the Petrol Heads with the least. These choices resemble the general environmental profile of the clusters, where Public Mobiles again comes as the second in ranking the importance of environmental attributes. Interestingly, Status Seekers are relatively stable across each attribute with perhaps the driving range as the most distinct one. However, they score the lowest in all three battery-charging related elements noting perhaps both their experience with EVs, but also the availability of other cars within the household. Curiously, this group is not driven by the environmental importance of EVs which could point toward the notion of having EVs as a symbol of status, but also to a disinterest of EVs as an environmental option as recent findings have noted that (high-end) PHEV buyers only drive using the fuel option and not the electric (Zarazua de Rubens et al. 2018).

Arguably, Figure 7, shows that all consumer clusters value EV attributes relatively equal, with the exception of the environmental importance, which points to the politicised nature of EV adoption and its direct link to the identity of each consumer and their relationship an environmental lifestyle. Therefore, EV adoption strategy should focus more on highlighting the technological profile of EVs instead of solely, with the exception of Tesla, their environmental attributes. This approach would allow EVs to appeal to a larger pool of consumers, as a technologically-driven vehicle. Moreover, its suggested that irrespective of the consumer’s identity towards environmentalism, all consumers have concerns towards battery-related elements as they graded them relatively equal. Therefore, policy and strategy should also focus on improving consumers knowledge about EV specifications and real-life performance, as it has been noted above that EVs would meet the majority of consumers daily driving requirements even in harsh winter conditions.

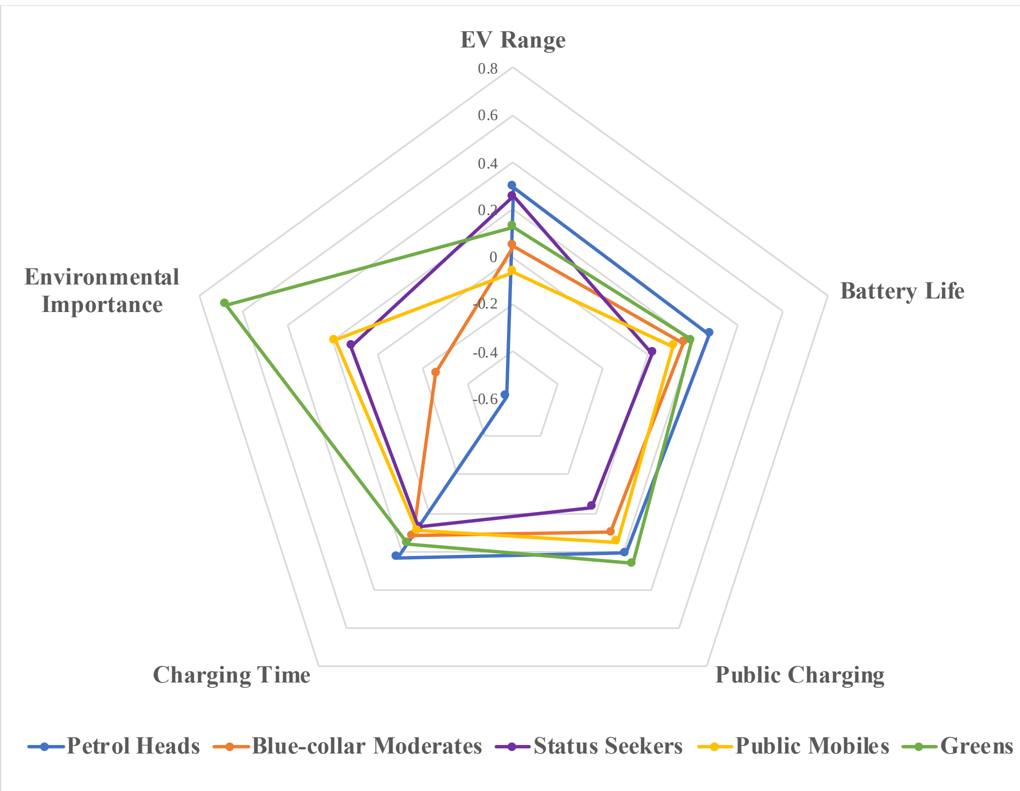

Figure 7. EV adoption clusters on EV preferences. Note: The figure does not include Cluster 5 (Sceptics), since this group sows a complete disinterest in all attributed (ranked at -2.5) which distorted the visuals of the figure.

In addition, the study investigated the respondent's and clusters knowledge and interest of vehicle-to-grid as shown in Figure 8. Status Seekers shows the most respondents with V2G awareness, which is perhaps not surprising considering this cluster has 70% of all EVs across the sample and also are technologically inclined. However, they ranked only fourth when it comes to placing the importance of V2G within the consideration of buying an electric vehicle. As such, it seems that education is not a barrier to V2G adoption for this cluster—instead, the benefits of V2G (e.g. renewable energy integration and economic savings) would more likely interest other clusters. For example, the Greens and Public Mobiles pro-environmentalism and the Blue-collar Moderates stated economic interests cause these clusters to rank V2G most importantly. These results show that V2G becomes an attractive element to those interested in environmental and financial attributes of vehicles and therefore V2G can contribute to make EVs more attractive to these mainstream consumers. However, since early adopters are somewhat disinterested in economic savings and environmentalism, V2G is not seen as important to for first adoption.

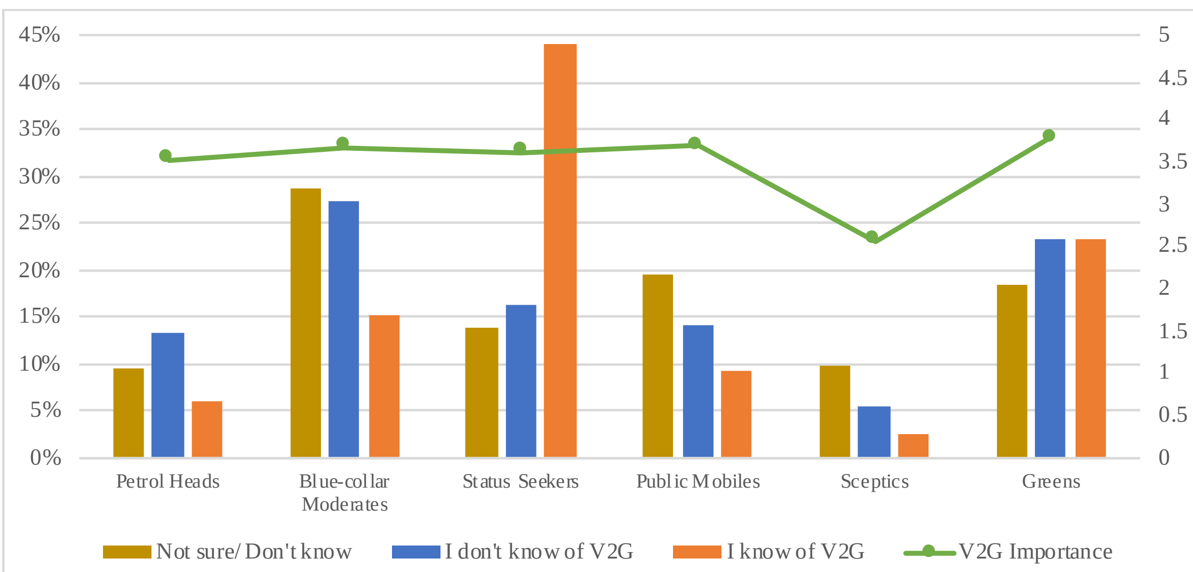

Figure 8. V2G knowledge vs V2G Importance. Note: Constructed by Author.

2.2.3.4 EV adopters across countries: an international comparison

Figure 5 shows the breakdown of customer clusters on each of the Nordic countries. Excluding Iceland, the other four countries seem relatively stable across samples. Curiously, it is that Norway is the country with the most respondents pertaining to Petrol Heads followed by Denmark and Finland, which points perhaps at the polarised automotive market in Norway where EV sales are around half of all new cars (Knudsen & Doyle 2018), meaning that there are still ~50% of the population is currently still purchasing petrol and diesel vehicles. This can point both at the lifestyle argument where Petrol Heads identity has become stronger as a result of EV penetration but also it could note other elements driving range being more coveted due to Norway's mountainous landscape and relatively lack of public transport interconnection between cities. Status Seekers on the other hand, are most present in Denmark and Norway, which may point to the countries higher perceived wealth per resident.

Nonetheless, the most evident observable result is that despite the considerably great disparity across these countries current level of EV adoption (only Norway is nearing 30%), the cluster composition indicates that the potential market for EV adoption is relatively equal across countries. Given the same customer composition, the analysis therefore highlights both the success of Norwegian EV policy specifically, but also the lack of effectiveness of the other country's governments in successfully integrate EV into national fleets. Moreover, it stresses the importance of policy-making to create a level-playing field for EVs, without favouring petrol and diesel options, as has been evidenced in other regional studies (Zarazua de Rubens et al. 2018). A clear implication is, thus, that consumers of the countries are not significantly different, and instead adoption appears to be primarily driven by the socioeconomic policy system put in place within each country.

In addition, it highlights how current policy strategy for EV diffusion that has focused in increasing environmental awareness, putting EVs as the cleaner vehicle option asking consumers to, even perhaps, pay a premium for it, has not resulted in effective EV adoption. Instead, as this paper shows, consumers across countries are relatively similar and thus policy should focus in making EV accessible to consumers and communicate EV specification attributes as a technological-driven vehicle, to appeal to the larger consumer pool.

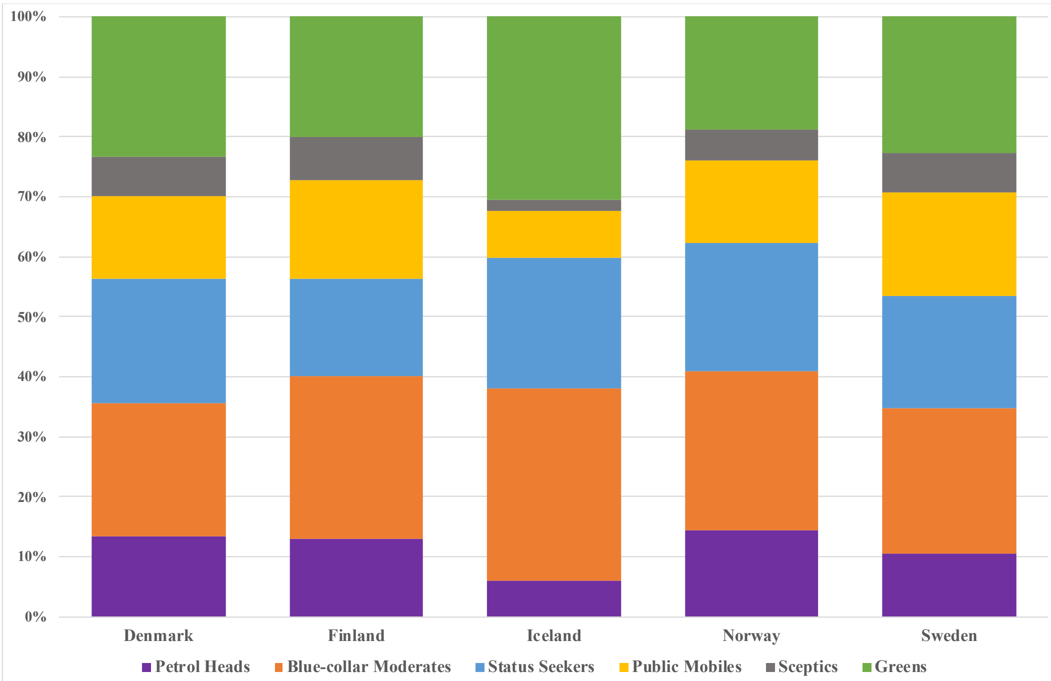

Figure 9. EV adoption clusters across countries. Note: Constructed by Author.

2.2.4. Discussion & Conclusion

Based on demographic and socio-economic characteristics, mobility and vehicle preferences and electric vehicle and vehicle-to-grid interests our results show that the automotive market, in the Nordic region, can be accommodated across six specific consumer clusters. In particular the three clusters of Status Seekers, Greens and Blue-collar Moderates are next most primed for electric vehicle adoption. The adoption of EVs by these clusters would lead to EVs moving to the mainstream market, as these clusters account for 68% of all consumers. Status Seekers represents the highest income earners, typically male, with a majority of respondents having postgraduate education, and are identified as the first adopters, corroborating previous research (Wolf & Seebauer 2014; Vassileva & Campillo 2017; Axsen et al. 2016; Neubauer et al. 2012; Plotz et al. 2014). Almost one third of Status Seekers already has an EV, the most across clusters, which still leaves 70% of this potential sub-market to be captured. These consumers, however, are more technologically driven than environmentally, and therefore EV strategies (i.e. promotion) aiming to reach this group should highlight the potentially superior technological attributes of EVs, such as newer technologies, acceleration and power efficiency.

The next two clusters, Greens and Blue-collar Moderates, together accounting for 48% of the total consumer pool, are interested in EVs for disparate reasons – environmentalism and economics, respectively. Particularly the Greens group shares many characteristics with early adopters, such as having the second highest income earners and the second most postgraduate educated respondents. This group showed the most stated interest on EVs (Figure 6), has the most environmentally-inclined consumers, and 90% of its driving respondents state to drive <50km/day, implying high suitability for EV adoption. However, considering more than two thirds are expected to buy their next car within the next 5 years, EVs would need to decrease in price within 5 years for this cluster to adopt. This is because, despite their pro-environmentalist and comparatively large dispensable income, this group currently has one of the lowest adoption rates which can be largely attributed at the current price of EVs, since 86% of these consumers expect to spend less than €30,000 in a car; and as seen in Table 12, only EVs like the Nissan Leaf in Norway and Iceland has been within this price to date. This apparent price sensitivity, however, is an interesting reaction considering Greens consumers show the second highest stated income but, unlike Status Seekers (21%), only 7% of consumers expects to spend €30,000-€40,000 in a vehicle, which is below even than the Petrol Heads and Blue-collar Moderates Clusters. Arguably, this points at Greens being value-sensitive, where as shown in Figure 7, these consumers are some of the most concerned with EV range and battery attributes and may have not considered current EV offerings worth investing. Apart from price, this group is mostly concerned with public charging, which contrast with their low daily driving requirements.

The second potential mainstream consumer group is the Blue-collar Moderates cluster, with an almost even gender gap and a lower earning income (4th among clusters). While this cluster is not environmentally driven, it showed the third most interest on EVs and has the current second highest adoption rate behind Status Seekers, mostly driven by the potential financial savings from the low cost of operation, as well as the EV as a new technology. Arguably these factors are related to the socio-economic profile of the cluster having the second youngest respondents interested in new-technologies but also their price-sensitivity, as shown in Figure 5 above. Price, however, is the main determinant for this cluster. More evidently, similar to the Greens cluster, 85% of its respondents consider a car of <€30,000. Therefore, unlike other studies that identified mainstream EV buyers as having low EV awareness (Axsen et al. 2016), the results of this study find that the potential mainstream EV adopters are the most interested on EVs however, price has kept these consumers out of the commercially available EV options.

The next three clusters, Petrol Heads, Public Mobiles and Sceptics are not expected to make a transition to EVs within the short-term. However, for both the Public Mobiles and Sceptics, it is mainly attributed for the lack of interest in vehicle ownership and in driving, as 69% and 53% of their respondents stated to not drive and over one third of each do not have a license. Considering, 98% of Public Mobiles and 55% of Sceptics are not expected to buy a new car at all, these groups are arguably continuing to move onto public modes of transport which inherently are also becoming full electric or hybrid (buses, trams, trains, taxis) (VR 2018; Electricity 2018). In our sample however, these groups combined account only for one fifth of respondents. Petrol Heads, our results suggest that will be the last to transition to electric mobility. Particularly, this cluster shows the second highest vehicle ownership rate across all groups, with over two thirds of their respondents expected to buy a car in the next 5 years. However, it is the only group with current zero percent EV adoption rate and shows the least stated EV interest. Nonetheless, just like with Status Seekers, this group is mostly attracted to attributes of speed, acceleration, comfort and size. Therefore, strategies to reach these consumers should focus on the technical attributes of EVs, as opposed to only the environmental characteristics.

Model	**Fuel Type**	**Price (€)**					**Range (km)**
		Denmark	*Finland*	*Iceland*	*Norway*	*Sweden*	
Tesla S (75D)	Electric	89,560	102,000	71,000	65,294	92,948	490
VW e-Golf	Electric	41,436	42,551	31,324	34,031	42,073	300
Nissan Leaf	Electric	34,765	35,900	27,676	25,615	35,927	378
Skoda Octavia	Petrol	30,336	23,418	26,566	28,958	20,813	1,020
VW Golf BlueMotion	Petrol	34,093	25,246	26,963	32,656	24,885	1,020
Peugeot 208	Petrol	17,448	15,996	20,143	20,719	15,302	1,022

Table 12. BEV and ICEV 2017 retail price and range comparison in the Nordic countries.
Note: Obtained from Noel, et. al, (2018) (Noel, Zarazua de Rubens, Kester1, et al. 2018).

The results from the customer clusters reveal three key elements regarding the price, the range and the environmental attributes of EVs and suggest a layered policy approach to EV adoption. First, that the mainstream market has yet to be reached due to the current price position of EVs, as this study has shown that, with the exception of Status Seekers (63%), between 84%-94% of respondents of each cluster expects to consider a vehicle of <=€30,000. To some extent, this indicates that mainstream markets will be soon reached as its commonly acknowledged that the price of EVs will continue to decrease, mainly due reductions in battery price but also in economies of scale (Knupfer et al. 2017). However, until that point, it would behove national governments to subsidise EVs such that they are between €20,000 and €30,000. Indeed, these governments may want to specifically consider decreasing subsidies such that the price of an EV is always around €25,000, even when battery prices decrease. Also, current EV adoption has arguably not been led by their environmental attributes and rather by the affordability and sense of status, considering that the Greens cluster is the most pro-environmental group and has the most stated EV interest but has yet to adopt EVs. This in turn suggests that current EV strategies should have been focused more explicitly on the technological attributes of vehicles, as opposed to solely their greenness, which is the case for EVs like Nissan Leaf. In turn, this study suggests that EVs like the Nissan Leaf have to-date missed on their prime markets with a vehicle that it is too expensive for the Greens and Blue-collar Moderates clusters (above €30,000), but it is not positioned with a technologically-driven profile to appeal to Status Seekers, as perhaps other like Tesla have done it.

Moreover, for driving range requirements, our sample shows that with the except of Status Seekers (64%), up to 90% of respondents of other clusters state to drive <50kms/day, and up to 97% of the sample states to drive less than 80kms/day. Corroborating that even in harsh conditions, EVs would still meet the driving requirements of the majority of people, without needing to charge during the entire day. Despite the technical sufficiency of an average EV, all of the clusters placed a moderately high importance on EV range, which may inhibit adoption. In addition to this, and considering all clusters placed a marginal importance in battery-related elements, policy should focus to better EV range education campaigns to create awareness that, even on its current form, EVs are a real vehicle option for most consumers. While investments in public charging network should be approached with caution, as budget available should be initially directed to making EV accessible, policy should consider improving public (and work place) charging infrastructure. Considering, currently, it is mainly the capital cities, such as Oslo and Copenhagen with a substantial network developed. For the late EV adopters, such as the Public Mobiles or the non-driving consumers of the Greens cluster, policy should look at electrifying public modes of transport. Particularly as these consumers show a high interest towards environmental attributes without interest in vehicle ownership or even driving.

Furthermore, the results show that V2G capability has the potential to increase the attractiveness of EVs to consumers, particularly those interested in environmental and financial attributes, which would comprise the mainstream consumers. As evidenced by the interest on V2G from the Greens, Blue-collar Moderates and Public Mobile clusters whose profiles are driven by environmental and financial attributes in vehicles and EVs. To-date most V2G commercial activity has remained within the fleets-space (Benjamin K. Sovacool, Noel, Axsen, et al. 2018), but our results shows there is potential for V2G to explore passenger vehicle markets, and in particular potentially contribute to increase EV uptake. Noting that, V2G will be particularly valuable for the next clusters adopting EVs, Greens and Blue-collar Moderates, and thus OEMs should consider including V2G capability on their commercially available EVs within the next 5 years, along with being below the €30,000 price boundary.

Finally, the international comparison corroborates the critical role of governments and industry policy creating a space for EVs to operate and equitably compete against petrol and diesel options. Despite the large disparity of the current level of EV adoption across the Nordic countries, the cluster composition (Figure 9) shows that customers within these countries are remarkably similar. As such, the success (or failure) of EV adoption is primarily a result of national policies, not different compositions of consumers within each country. Therefore, these findings call for governments to re-visit transport policy in order to create a space in which EVs can operate competitively, if electric mobility is to be a key part of the decarbonisation of transport sector.

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3. Theme 2: the meso-level

The second research question is answered by introducing the following articles:

1. Noel, L., G. Zarazua de Rubens, J. Kester, and B. Sovacool. (2018). '*Understanding the Socio-technical Nexus of Electric Vehicle (EV) Barriers: A qualitative discussion of Range, Price, Charging and Knowledge.*' Under review with Energy Policy.

2. Noel, L, Zarazua de Rubens, G, Kester, J & Sovacool, B. (2018), *'Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)' Transport Policy*, vol. 71, pp. 130-137.

These articles relate to the investigation of the structural barriers and benefits of electric vehicles and vehicle to grid. The first article focusing on undercovering the entire array of challenges EV face, including technical and non-technical elements. Whereas the second article focuses on the benefits of both EVs and V2G to undercover the value-capturing potential from these technologies.

3.1 Understanding the Socio-technical Nexus of Nordic Electric Vehicle (EV) Barriers: A Qualitative Discussion of Range, Price, Charging and Knowledge

The third article introduced in this dissertation (and first of these theme) considers that the transition towards the electrification of transport has not made equal progress globally and has faced several impediments to consumer adoption of EVs across the Nordic region and beyond. While there has been a multitude of reasons provided in the literature, we aim to characterize the barriers that remain to electrification today, as well as their perceived interconnections and futures. To provide insight into this query, the authors conducted 227 semi-structured interviews with transportation and electricity experts from 201 institutions across seventeen cities in Denmark, Finland, Iceland, Norway, and Sweden. The qualitative results and consequent cluster analysis shows that common barriers like range, price and charging infrastructure continue to persist, despite technological advancements over the recent years. At the same time, results also show that barriers are highly interconnected and commonly connected to consumer knowledge and experience. The article concludes with a discussion of policy implications of the findings and potential future research.

3.1.1. Introduction

Electric vehicles (EVs) are seen as an important tool in the sociotechnical transition towards the decarbonization of transportation, along with capturing other co-benefits associated with local health emissions, reduced oil dependency and noise pollution (Noel, Zarazua de Rubens, Kester, et al. 2018; Egbue & Long 2012; Sovacool & Hirsh 2009). The global importance of EVs has been legitimized in recent years, at a governmental level, with most major economies setting EV penetration targets in the short (2020), medium (2030) or long term (2050), and at industry level, with most automotive manufacturers announcing the introduction of one or several EV models by 2020; which has seen EV market surpassing the 2 million global penetration milestone in 2016 (IEA 2017). Nonetheless, while EVs have continued to make technological advancements and adoption progress, they continue to face a variety of impediments and have not yet made a substantial mark on the global vehicle fleet, accounting for only 0.2% of the total passenger vehicle fleet by the end of 2016 (IEA 2017). As a result, there has been a lot of focus, particularly in academic spheres, with a wide variety of articles investigating the barriers to EV adoption, aiming to explore the lag in EV sales as compared to the climate and health benefits they purport, with a selected few articles shown in Table 1 (which are from both the perspectives of experts as well as consumers).

The central barriers identified in the academic literature are mostly technical or economic. Indeed, common across the literature has been a focus on range, price and charging infrastructure as the techno-economic elements impeding wide-scale EV adoption. For example, limitations in battery capacity constrains the driving range of an EV and the simple increase of the physical size of the battery is not a sustainable or cost-effective solution (Neubauer et al. 2012), and likewise, incentives to address battery limitations may not be cost effective either (Silvia & Krause 2016; Noel & Sovacool 2016). Alternatively, the continued improvements on energy density of vehicle battery packs still necessitates substantial scientific and technological development and faces limited ceilings of development (Thackeray et al. 2012). Non-technical elements, however, such as social and business practices or political interests, have also been identified as barriers to electrification, these being more complex to overcome (Sovacool & Hirsh 2009). In this light, the literature has more recently tended to focus on consumers, often with limited experience with EVs, to explain barriers in EV adoption (Rezvani et al. 2015). As such, much of the current literature looks to explain the barriers that individual consumers encounter when purchasing EVs, either using qualitative methods (Schuitema et al. 2013; Franke & Krems 2013; Egbue & Long 2012), or also commonly, choice experiments to analyse willingness-to-pay for electric vehicles (Jensen et al. 2013; Hidrue et al. 2011). So, while the literature identified barriers that are mostly technical or economic, there is also identification that consumer's behaviour, knowledge and perceptions play a role in EV adoption.

This paper aims to explore an assortment of the barriers that EVs face as well as defining particularly the nexus that exists between the major techno-economic and consumer knowledge barriers, a nexus that we have termed 'socio-technical' (Geels et al. 2017). As compared to the literature presented in Table 13, this paper adds four novel contributions to the literature. First and foremost, the authors conducted 227 semi-structured interviews with participants from 201 institutions across seventeen cities in the five Nordic countries, whereas the sole previous expert interview focused on the UK and Germany, had a much smaller sample size (13 compared to 227), and is potentially outdated given how fast EV technology develops. Secondly, this paper is the first to develop a nexus of barriers and show the interconnectedness of a large variety of barriers. Thirdly, the results identify topics considered by experts to be either no longer or will soon not be a barrier. Fourthly, this paper offers a first to attempt to characterize a comprehensive perspective of EV barriers, and discusses a total of 53 barriers, some of which are not previously discussed in the literature, especially beyond those at the top of the list (such as range, price, or charging infrastructure).

While the interviewees define electric vehicles, experts generally referred to either light private passenger battery electric vehicles (BEV) or plug-in hybrid electric vehicles (PHEV), but also accounted of other forms of electric mobility such as fleets and public transportation. Selected experts were from national government ministries, agencies, and departments; local government ministries, agencies, and departments; regulatory authorities and bodies; universities and research institutes; power transmission, distribution and supply utilities; automobile manufacturers and car dealerships; private sector companies; and industry groups and civil society organizations. We then analyse this dataset using a mix of methods including qualitative analysis and cluster analysis.

The research is placed in a Nordic context as these nations have traditionally been positioned at the top various indicators in favour of EV diffusion (for example, that they can afford EVs, often considered an expensive technology), as well as being recognised for pushing aggressive decarbonization agendas within the energy and transport sectors (Sovacool 2017). For example, by 2016, Norway and Sweden being the first and third nations in terms of national EV market share, with 29% and 3.4% respectively (IEA 2017); or Norway and Denmark offering the highest electric vehicle purchase subsidies (Hertzke et al. 2017). The aim is to investigate and reflect how even within such advanced economies, EVs still face a multitude of barriers, and many of these include both technical and non-technical elements. Therefore, this research serves as a means of reference for other nations aiming to endeavour in EV technology as a tool within their decarbonization agendas.

Author	Citation	Year	Method	Central Barriers
Sovacool et al.	(Sovacool and Hirsh 2009)	2009	Qualitative literature review	Price, consumer knowledge, institutional inertia
Hidrue et al.	(Hidrue et al. 2011)	2011	Survey	Range, Charging Time, Price
Axsen & Kurani	(Axsen and Kurani 2011)	2011	Survey	Range, Public charging, Immature Technology, Price
Egbue & Long	(Egbue and Long 2012)	2012	Survey	Range and price
Flamm & Agrawal	(Flamm and Agrawal 2012)	2012	Focus Group	Price, worse technology, charging infrastructure

Graham-Rowe et al,	(Graham-Rowe et al. 2012)	2012	Consumer Test Drive and Interview	Price, performance, range, aesthetics, symbolic value
Steinhilber et al.	(Steinhilber, Wells, and Thankappan 2013)	2013	Expert Interview	Government policy, charging infrastructure, business models
Schuitema et al.	(Schuitema et al. 2013)	2013	Survey	Range, consumer perceptions
Sierzchula et al.	(Sierzchula et al. 2014)	2014	Regression Model	Price (subsidies) and charging infrastructure
Rezvani et al.	(Rezvani, Jansson, and Bodin 2015)	2015	Literature Review	Consumer perceptions & knowledge, price

Table 13. Summary of literature regarding EV barriers. Note: Constructed by authors

3.1.2. Research Methods

To explore the barriers surrounding electric mobility in a more holistic and qualitative manner, the authors relied primarily on original data collected through semi-structured research interviews. This methodology was applied on a regional context taking the five Nordic countries as place of study, since it is recognized that these countries have traditionally had progressive push of climate, energy and transport policy agendas emerging as leading nations in electric vehicle uptake (Norway), or pioneers of wind energy (Denmark), or geothermal energy (Iceland).

The implementation of *semi-structured interviews* refers to the collection of the data for this study, by asking semi-structured questions to participants. This methodology allows the authors to have guidance and flexibility, by asking a set of fixed questions to then, create a conversational channel of information-gathering, allowing space for spontaneous responses that add depth and in some instances unforeseen narratives to the research (Harrell & Bradley 2009). These semi-structured form of interviewing is suitable when the objective of the research is to understand complex elements and their intersection with perceptions, beliefs, and values (Yin 2003). Lastly, the authors selected this research method as it allowed for novel and up-to-date data (at the time of the interview) which was not available in other formats, since official documents can take months or even years to be published.

The authors conducted 227 semi-structured interviews with participants from 201 institutions across 15 cities in the five countries of Denmark, Finland, Iceland, Norway and Sweden from September 2016 to May 2017. Those interviewed were selected to represent the diverse array of stakeholders involved with transport technology, policy and practice, and included members of:

- National government ministries, agencies, and departments including the Ministry of Industries & Innovation (Iceland), Ministry of Environment and Energy (Sweden), Ministry of Finance (Finland), and Ministry of Taxation (Denmark):
- Local government ministries, agencies, and departments including the Akureyri Municipality (Iceland), City of Stockholm (Sweden), Aarhus Kommune (Denmark), City of Tampere (Finland), City of Oslo (Norway), and Trondheim Kommune (Norway);
- Regulatory authorities and bodies including the National Energy Authority (Iceland), Danish Transport Authority, Icelandic Transport Authority, Helsinki Regional Transport Authority (Finland) and Trafi (Finland);
- Universities and research institutes including the University of Iceland, Swedish Environmental Institute, DTU (Denmark), Aalborg University (Denmark), VTT Technical Research Centre (Finland), NTNU (Norway), and the Arctic University of Norway;
- Electricity industry players such as ON Energy (Iceland), E.ON (Sweden), Vattenfall (Sweden), Energinet (Denmark), DONG (Denmark), Fingrid (Finland), Elenia (Finland) and Statnett (Norway);
- Automobile manufacturers and dealerships including the BMW Group (Norway), Volvo (Sweden), Nissan Nordic (Finland), Volkswagen (Norway), and Renault (Denmark);
- Private sector companies including Siemens Mobility (Denmark), Nuvve (Denmark), Fortrum (Finland), Virta (Finland), Clever (Sweden), Nordpool, (Sweden), Norske Hydrogen (Norway), Microsoft (Norway) and Schneider Electric (Norway);
- Industry groups and civil society organizations such as the Danish Electric Vehicle Alliance (Denmark), Finnish Petroleum and Biofuels Association, Tesla Club (Finland), Power Circle (Sweden) and the Norwegian Electric Vehicle Association.

Interviews lasted generally between thirty and ninety minutes in their duration, and participants were, among others, asked the question: “What are the of barriers that electric vehicles currently face?”. The following context in the interview was developed according to the background of each respondent. Participants were not prompted for responses and were allowed to provide answers as long or as detailed as they wished. Likewise, we did not define any terms and allowed broad discussion of each topic, meaning some experts discussed electric vehicles in the context of personal transportation, but also other types of vehicles, such as buses or heavy-duty trucks. Each expert encounter was recorded, with the authorization of the respondent, and then fully transcribed. Each interview was also given a unique respondent number (which we refer to whenever presenting interview data, Appendix 6.4).

Admittedly, the non-random sample relied upon for primary data is limited in several ways. For example, interviews were constricted to researchers that spoke English, moderated by locations visited, and may suffer from potential selection bias. Likewise, the data from the interviews is presented here as *anonymous* to encourage candour and prevent retaliation. Although participants were therefore guaranteed anonymity, Appendix I offers a high-level summary of the interview respondents. Finally, the research was *grounded* in the sense that we commenced our project without any preformed hypotheses (Geertz 1970; Strauss and Corbin 1990). The reasoning behind this was that we maintain a grounded approach helps minimize interpretative bias caused by researchers trying to force responses into present cognitive frameworks (Blaikie, 2000, Cook and Campbell, 1979).

After collection of the interview data, each interview was subsequently fully transcribed, and then coded in NVIVO. The data was coded with grounded theory in mind, meaning that the coded themes for each discussed topic were not predetermined, but based on the data available. Below we present quotes and the themes which were coded in NVIVO. In addition to the descriptive analyses, we also utilized a cluster analysis for Figure 10, shown below, based on the coded similarity between each of the coded themes across our interviews. In other words, to what extent a theme returns in other interviews and with which other coded themes. This analysis was conducted by using NVIVO, and it utilizes a Jaccard's coefficient of similarity (Jaccard 1901), a metric for comparing shared similarity between two disparate data sets, implying a larger value has a larger share of coding similarity, i.e. the themes were more closely related.

Admittedly, our qualitative approach does possess shortcomings. The qualitative aspect of interview responses makes them difficult to code and answers understandably varied for each participant. Some respondents may have provided socially desirable responses, telling us what they think we wanted to hear. Others could have deliberately given answers that they thought would sway the outcome of the study in their favour. Inaccuracies could also arise due to poor recall and memory of the interviewee (Kroes and Sheldon 1988). We have attempted to minimize these shortcomings by validating their findings with a secondary method, that of a literature review, and by triangulating responses within the sample (i.e., not presenting only minority opinions).

3.1.3. Results & Discussion

We aim to present the barriers from our body of evidence in a novel way. In addition to keeping track of barriers the experts discussed for EVs, we also noted when respondents either explicitly said a certain topic was *not a barrier*, as well as when it would *soon not be a barrier*. Both of these were unprompted, as experts were only explicitly asked what is a barrier to EV deployment.

There was a wide variety of barriers to EVs suggested by the experts, with a total of 53 different categories of barriers, as summarized in Table 14. In addition to a variety in aggregate, individual experts offered many suggestions of the obstacles EVs faced, as each expert suggested on average over 4 barriers. As such, experts often weaved barriers together characterizing one barrier as dependent on another. Implicit in this is that there is not just one barrier holding back EVs, even among those who disagree which barriers are the central ones. Moreover, the barriers encompassed a variety of topics, including technical (range and impacts to grid), economic (price, consumer incentives), social (consumer knowledge, political will), business/industrial (OEM disinterest, business models), and environmental (winter weather).

No.	Barrier	Number of respondents	Percentage of Experts
1	Range	136	59.9%
2	Price	130	57.3%
3	Public charging infrastructure	110	48.5%
4	Consumer knowledge, mental barriers	95	41.9%
5	Apartment charging	49	21.6%
6	Lack of incentives for consumers	45	19.8%
7	Lack of car models	39	17.2%
8	Impacts to Grid	37	16.3%
9	Winter Weather	36	15.9%
10	Lack of political will	28	12.3%
11	Long Charging Time	25	11.0%
12	Can't afford to subsidize EVs	21	9.3%
13	Turnover Rate	18	7.9%
14	Home, Work Charging	14	6.2%
15	Battery Technology	12	5.3%
16	Resale Value	11	4.8%
17	Battery life	10	4.4%
18	Battery recycling	10	4.4%
19	Business Models	10	4.4%
20	Just a matter of time	10	4.4%
21	Waiting for better EV	9	4.0%
22	None	9	4.0%
23	OEM disinterest	9	4.0%
24	Charging standards	8	3.5%
25	Material Constraints	8	3.5%
26	OEM production capacity	8	3.5%
27	Battery production	6	2.6%
28	Biofuel industry	6	2.6%

29	Dealership disinterest	5	2.2%
30	Worse Performance	5	2.2%
31	Developing the 'EV Ecosystem'	4	1.8%
32	Electricity Taxation	4	1.8%
33	Public charging too complex	4	1.8%
34	Actor knowledge, willingness	3	1.3%
35	Conservative utilities	3	1.3%
36	Battery Fires & Safety	3	1.3%
37	EV availability (i.e., certain EV models not sold within country)	3	1.3%
38	Reliability	3	1.3%
39	Demand charge	2	0.9%
40	Distrust of car producers	2	0.9%
41	Increasing use of conv. electricity	2	0.9%
42	Low amounts of EVs within country's current vehicle fleet	2	0.9%
43	Business development	1	0.4%
44	Commercial vehicle constraints	1	0.4%
45	Displacing public transportation	1	0.4%
46	Heavy Transport	1	0.4%
47	Misinformation, lobbying against EVs	1	0.4%
48	No smart charging capability	1	0.4%
49	Not paying fuel, road tax	1	0.4%
50	Oil Industry	1	0.4%
51	Rather use other fuels, technology	1	0.4%
52	Tires wearing more quickly	1	0.4%
53	Well-to-wheel emissions	1	0.4%

Table 14. Summary of 53 Barriers to EVs Identified by Expert Interviews (n=227).

Consequently, as shown in Figure 10, a clear nexus was formed from the connections between the primary barriers (discussed by more than 25% of respondents) and even with secondary barriers (less than 25% of respondents). Here we propose the nexus of barriers comprised of range, price, public charging infrastructure, and mental barriers or knowledge. This nexus of four barriers is important because it represents both the most discussed barriers (as shown by the size of the circle), and also the most interconnected barriers (as shown by the connecting lines), implying resolution of other secondary barriers may be dependent on resolving the central four barriers in the nexus. The first three aspects of the nexus, range, price and public charging infrastructure fit squarely within the techno-economic on which the literature often focuses, and were also the three most commonly discussed barriers. At the same time, each of these were the three most commonly discussed topics for those either explicitly not a barrier or perceived to soon not be a barrier, as shown in Figure 11. We discuss each of the four aspects of the nexus in turn below.

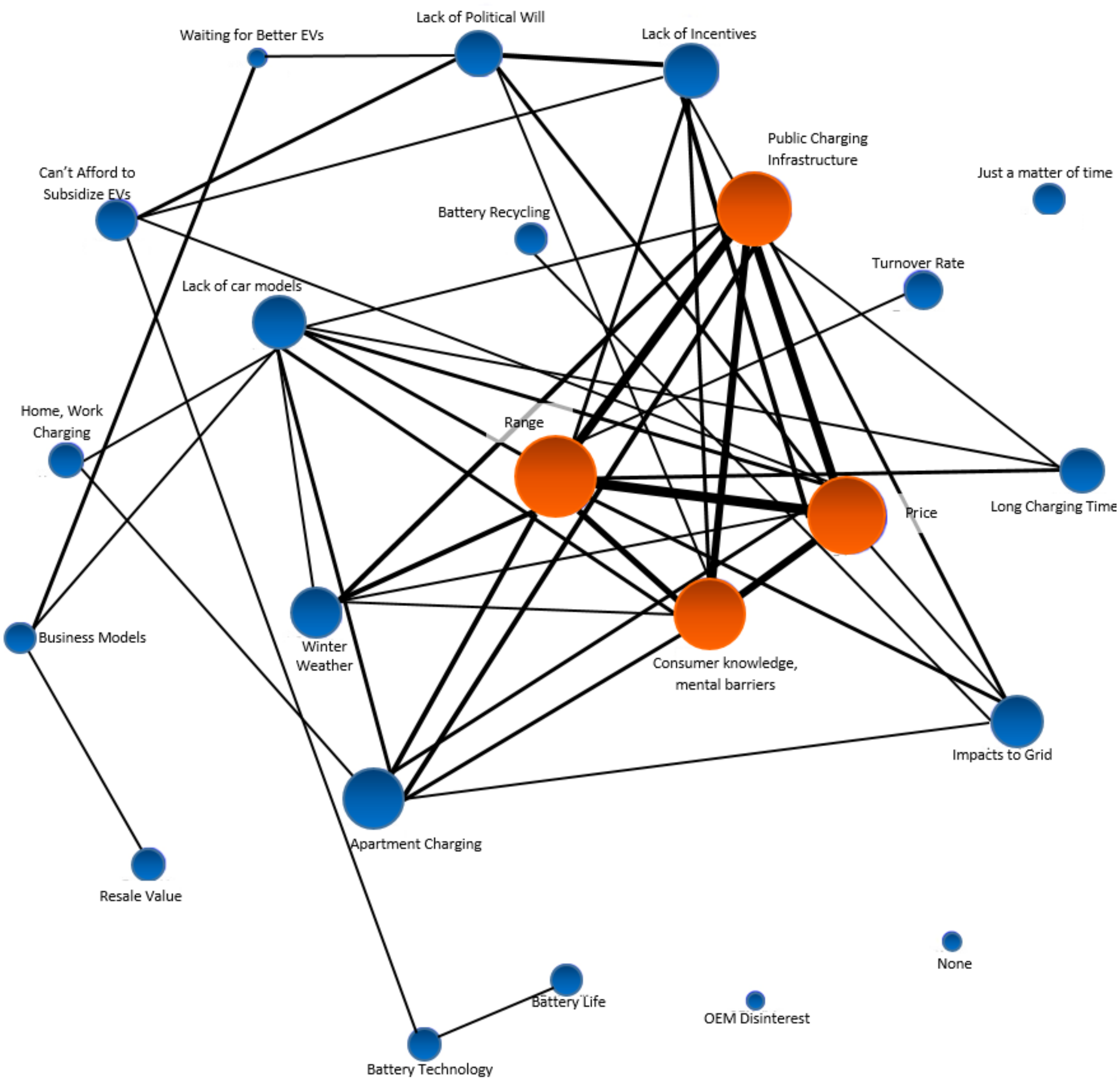

Figure 10. Cluster analysis of EV barriers, with proposed nexus demarcated by the color orange (for identification). Circle size shows respondent frequency (showing only those discussed by 4% or more of respondents), line thickness based on Jaccard's coefficient of similarity (J≥0.1). The figure does not show the entirety of barriers displayed on Table 2. Note: OEM = original equipment manufacturer.

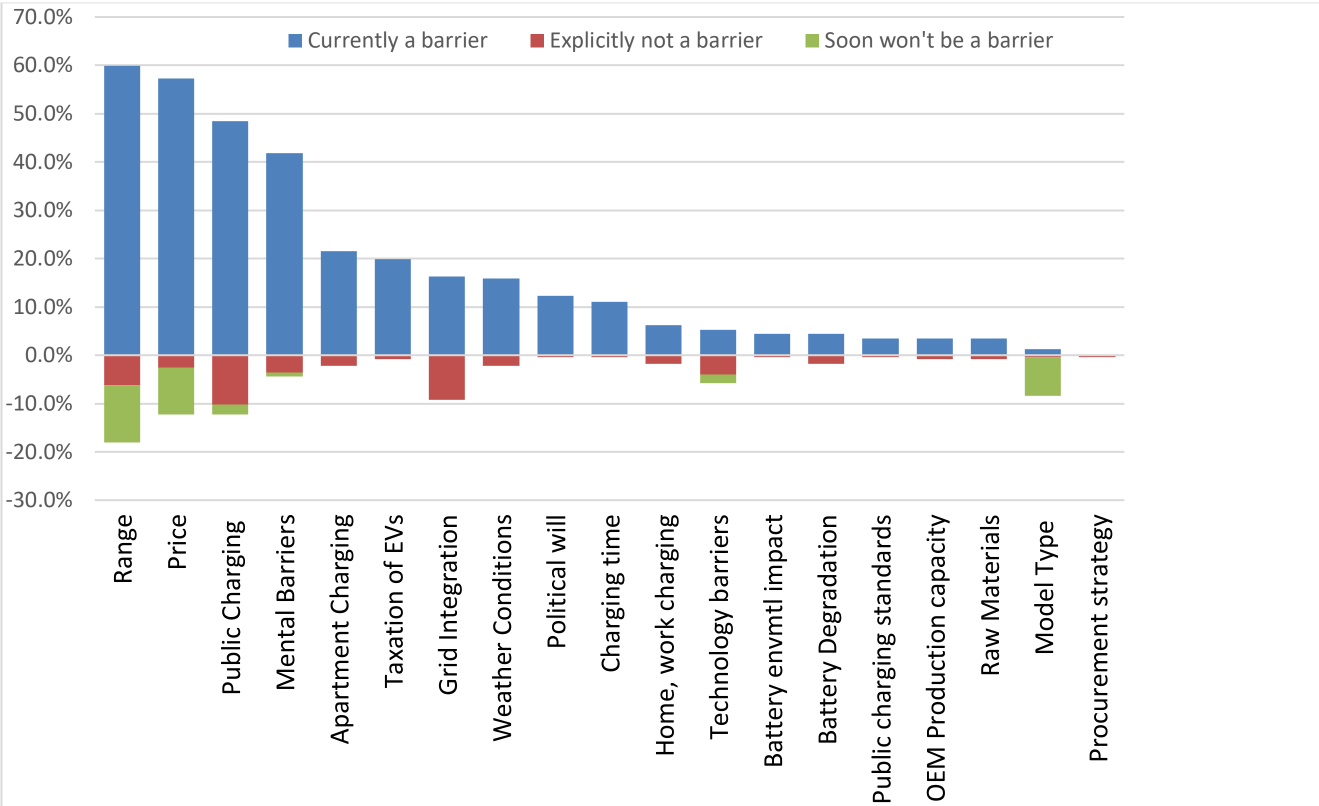

Figure 11. Barriers and Non-barriers Identified by interviews (only includes topics discussed as both barrier and non-barrier). Note: Constructed by authors.

In addition, there is some differentiation of these barriers across the countries. In Table 15, we show how the top ten barriers are distributed across the five Nordic countries (the remaining 43 barriers had little variation and dwindling denominator, thus were omitted). Though there is relative consistency throughout these barriers, there are three notable exceptions. First, a comparatively low percent of experts in Norway mentioned price, which makes sense given their generous EV subsidies. Second, Denmark presents a special case, primarily because at the time of the interviews the Danish government had started to phase out earlier tax benefits (at the time of writing these were halted again), which explains the Danish expert's markedly higher response rate on *EV taxes* and *lack of incentives*. Also because of the low rate of concern about public charging infrastructure, which might be explained in line with leftover charging infrastructure from previous EV companies (Noel & Sovacool 2016), and relative smaller country. Lastly, Swedish experts had a much higher response rate for *consumer knowledge* and *apartment charging*. Possibly it stems from the Swedish car market, which is heavily influenced by the presence of Volvo; both in relation to a consumer focus on buying Volvo and in relation to the resulting low level of taxes on cars in Sweden, which makes consumer knowledge about EVs and a willingness to buy more important (as indicated by the attention to *price*). Regarding *apartment charging*, Swedish experts believed this to be the next big and so far unresolved challenge, with a large proportion of Swedes living in apartment buildings (see Section 3.5).

Barrier	Iceland (n=27)	Sweden (n=42)	Denmark (n=44)	Finland (n=49)	Norway (n=60)	Total (n=221)
Range	56%	64%	66%	57%	62%	61%
Price	56%	76%	73%	78%	22%	59%
Public charging infrastructure	56%	62%	23%	53%	55%	50%
Consumer knowledge, mental barriers	41%	67%	41%	41%	30%	43%
Apartment Charging	22%	43%	11%	16%	20%	22%
Lack of incentives for consumers	7%	7%	61%	24%	2%	20%
Lack of car models	22%	21%	9%	8%	27%	18%
Impacts to grid	7%	10%	16%	16%	27%	17%
Winter weather	11%	2%	9%	35%	18%	16%
Taxes on EVs	0%	0%	59%	8%	0%	14%

Table 15. Differentiation of Barriers by Country, as shown by percent of interviews discussing each barrier. Note that the total n is equal to 222 (not 227) because five interviews did not discuss any barriers to EVs. Constructed by authors

Finally, we show the frequency of each barrier discussed differentiated by the respondent's expertise (see Table 16). Similar to Table 15, we focus on the top ten barriers. While the general trend is the same across the different categories, i.e. range, price, public charging and consumer knowledge are generally among the top four most pertinent barriers, there are a few notable exceptions. For example, experts within the environmental/climate change field and the energy/electricity system field both discussed price more commonly than range. More interestingly, those with a transport background (transport system experts/EV industry) discussed consumer knowledge barriers the most, while those with an energy, environment and funding background discussed consumer knowledge the least. Outside of the top four barriers, overall trends also remain mostly similar.

Challenges	Transport, City Planning (n=72)	Energy, Electricity (n=61)	Funding, Investor (n=10)	Enviro, Climate Change (n=12)	Vehicle Researcher (e.g. fuel efficiency) (n=19)	EV, EVSE Industry (n=34)	Other (n=13)	Total (n=221)
Range	74%	49%	60%	50%	63%	56%	69%	61%
Price	68%	51%	60%	58%	63%	56%	38%	59%
Public Charging	47%	56%	60%	42%	37%	47%	62%	50%

Consumer Knowledge, Mental Barriers	51%	28%	20%	33%	47%	53%	62%	43%
Apartment Charging	22%	18%	10%	17%	26%	35%	15%	22%
Lack of incentives for consumers	28%	23%	20%	8%	0%	24%	0%	20%
Lack of car models	18%	11%	10%	17%	37%	26%	0%	18%
Impacts to grid	11%	28%	10%	17%	5%	18%	15%	17%
Winter weather	17%	21%	30%	8%	11%	9%	15%	16%
Taxes on EVs	22%	13%	0%	0%	0%	18%	0%	14%

Table 16. Differentiation of Barriers by Expertise, as shown by percent of interviews discussing each barrier. Note that the total n is equal to 221 (not 227) because six interviews did not discuss any barriers to EVs. Constructed by authors.

However, one should note that those working more closely to vehicles (Vehicle Researchers and the EV/EVSE industry) discuss the lack of EV car models as a more pertinent barrier, which is less recognized by other groups. Similarly, Vehicle Researchers did not discuss lack of consumer incentives at all, whereas this was a pressing concern for Transport experts/City planners as well as those within the EV/EVSE industry. Clearly, perceived barriers depend on the respondent's particular expertise (or experience), and each expertise's knowledge complement each other, providing a deeper understanding of EV barriers.

3.1.3.1 Vehicle Range

Range was by far the single most discussed barrier of EVs, brought up by practically 60% of respondents. This issue is exacerbated by the fact that experts saw the long distance of the Nordics, in terms of geographical dimensions and sparsely populated areas, to be one the greatest challenges for transportation in general. Range was commonly acknowledged as being sufficient for most driving, as is also noted in the literature suggesting they are adept for about 85% to 98% of drivers, depending on various criteria (Zhang et al. 2015; Saxena et al. 2015; Pearre et al. 2011b), but a challenge for the seldom yet very long trips, like when the car is used for a road trip vacation, as R112 describes:

> *"Then it's about driving distance, if you want to have only one car as private family and you want to go southern Italy on your summer holiday, it's difficult."*

Particularly in Finland and Norway, it was also common for the experts to discuss range in context of reaching their summer cottage. As R135 of Finland says:

> *"Let's say, we are country with long distances. If you just drive around the Helsinki*

Metropolitan area, that's fine, a range of 40 km is fine. But if you have the summer cottage, or you drive 500 km to your parents, it is not working."

Likewise, R175 connects range to the Norwegian love of nature and reaching their cabins:

"Norwegians are a nature loving country, and our country side is among, we have the mountain range in the middle. So in general people enjoy going to a cabin in holidays. That's when the real challenge are showing up with electric mobility."

Moreover, many experts expected this barrier to continue until EV ranges could compete to various levels of internal combustion engine vehicles (ICEVs). However, the estimate of the necessary increases to the range of EVs were diverse, and appeared to be connected only to comparisons to ICEVs. Some estimates of range were tamer, with experts expecting a range of 300 kilometres to be enough, as R31 proposes:

"So if you get to the border around 300 kilometres on a battery pack, that will be sufficient."

However, the majority of experts believed that the requisite range was substantially higher, somewhere between 400 and 600 kilometres. For example, R6 claims that at 400 to 500 kilometres range people will begin to consider EVs:

"Then if autonomy of four or five hundred kilometres and the possibility to charge your car – with battery infrastructure, as is being emphasized now, I think people would consider having an electric car as the only car."

R206 adds that once the range of EVs reaches 500 to 600 kilometres, there isn't a reason for consumers to reject EVs:

"Because when all the electrical cars have a range for 500 or 600 kilometres there is no reason to buy a gasoline or diesel car, so I think the range is the highest priority."

Finally, on the extreme end however, R167 believed that the range needed to compete with diesel vehicles:

"I think the main barriers are still range and the time it takes to refuel. Or a combination of that. Because if you had, like my diesel engine has got 1000 km of range. So, if you had 1000 km of range, it wouldn't be a problem. Or if it only took three minutes to refuel, it wouldn't be a problem you. But I think it is a combination of those."

While many experts recognized that range of EVs only rarely posed a challenge, particularly given the short distances of daily commuting, many still maintained that this was the central challenge. For example, R93 noted that even though they had experience driving EVs and knew it was only a handful of times that range posed any sort of challenge, they still faced range anxiety as a barrier:

> *"And I know it from myself, it's around 8 times in a year that I drive more than that. But still I have this range anxiety, that 'ohh, do I have sufficient [charge]', right? But it is a limitation."*

As a result, some viewed PHEVs as the solution to range anxiety, even if only to cover those few additional trips EVs would not be able to make. Although R76 characterized range as a mental barrier that would only affect a small portion of total trips taken, they still preferred PHEVs as a solution:

> *"Of course, the negative. You have the range anxiety that I'm sure you've heard a lot of people talk about. But personally I think the plug in hybrids are going to be the gateway to, the stop-gap until we really see electric vehicles. For those people that have the range anxiety, I think the plug in hybrids."*

R63 offered another, easy but potentially unpopular solution to this challenge, that is, to rent an ICEV for these seldom trips:

> *"So, they say 'no that wouldn't work for me because I want to drive to my cabin three times a year. Then, I can't have this car'. But actually then I would argue that you can actually rent a car for special occasions, because you don't need a super car that does everything if you don't use it like that all the time."*

On the other hand, in terms of non-private transportation, range was characterized not as a seldom problem, but rather a preeminent one, as R62 notes for heavy transportation:

> *"But you know the range is the biggest problem. If you want to transport like 40 tonnes on a lorry and you want to get the same range as a diesel lorry, with batteries, the current energy density you would need to fill of 30 of those 40 tonnes with batteries. Long hauling transport, it's a big issue, where electric may not be a feasible option, at least not for the overseeing time."*

However, for private transport, the fight seemed to be on focusing extending the range of EVs to mirror ICEVS. Nonetheless, R186 cautioned that continuing the fight to extend range was not only never-ending, but also inefficient (as you would be carrying around extra battery weight), instead the focus should be on adjusting expectations:

> *"So the discussion for the future is: do you need [that range]. AI guess we will somewhat stabilize on the range about five hundred or six hundred kilometres in the future. But if you're going eight hundred kilometres, that's still not enough [for some. The] next barrier is people getting used to living with it. Understanding it and using the technology right."*

Further complicating matters, range was also the barrier that was described by the most experts as *not a barrier*, as 18% of experts explicitly saying it was either not or soon will not be a barrier. The vast majority of these experts, however, viewed range not being a barrier *soon*, with 12% of experts saying it would no longer be a barrier in the near future, compared to 6% of experts saying it is already not a barrier. Though these experts believed it wouldn't be a barrier in the future, the time frame was usually relatively short. For example, R28 believed the range issue would be resolved within two years:

> *"So, I think within 2 years we will have better range in the cars and also we will have the grid completed [referring to EV charging infrastructure]. So, yeah. Two years, there will be nothing stopping people for owning electrical cars."*

Similarly, R70 believed that both the range and price barriers will be resolved by 2020 as more OEMs transition to electric vehicles:

> *"We see that happening right now. But until 2020 it's not going to take off. It's not going to be the market before 2020. We want to see take off with [Tesla] models 3, if they can produce enough cars and meet their goals the model 3 would certainly be big enough and would put a lot more electric cars on the roads. But we need more models and more companies to do this. Luckily, we see that by 2020, VW and Mercedes and all the big companies are coming out will electric cars with a long range at a reasonable price."*

However, some of the experts believed that there was no barrier, due to the technical sufficiency of EVs to make the wide margin of trips. As R100 notes, the vast majority of the Danish population would never go beyond further then the range of current EVs:

> *"I mean, it is cold now, but my Zoe is the new one with the 41 KW battery and I'm doing 200km in this weather [in February] which in Denmark is more than enough for 95% of the population which never goes beyond that. So we have the technology, and there's no barrier in the technology."*

Noteworthy, of the experts that did not believe range to be a substantial barrier, they often connected range to the barrier of consumer knowledge and, similarly, experts attached the range element to many of the other 52 barriers discussed; suggesting a nexus of interconnected barriers electric vehicles face as shown in Figure 10 above.

3.1.3.2 Vehicle Price

The second most common barrier discussed by experts was price, representing 57% of experts. Price was often an obvious barrier, given that the capital costs of EVs could be often as high as twice the cost of a comparable ICEV, as shown in Table 17. This challenge was compounded by the conceptualization of the EV as a secondary car or an inferior car, due to its perceived technical limitations. For example, R154 articulates that no one would be willing to pay twice as much for less of a car:

> "*They are too expensive, nobody is going to pay 40,000 euros for second car.*"

Model	**Fuel Type**	**Price (€)**					**Range (km)**
		Denmark	*Finland*	*Iceland*	*Norway*	*Sweden*	
Tesla S (75D)	Electric	89,560	102,000	71,000	65,294	92,948	490
VW e-Golf	Electric	41,436	42,551	31,324	34,031	42,073	300
Nissan Leaf	Electric	34,765	35,900	27,676	25,615	35,927	378
Skoda Octavia	Petrol	30,336	23,418	26,566	28,958	20,813	1,020
VW Golf BlueMotion	Petrol	34,093	25,246	26,963	32,656	24,885	1,020
Peugeot 208	Petrol	17,448	15,996	20,143	20,719	15,302	1,022

Table 17. BEV and ICEV retail price and range comparison in the Nordic countries. Constructed by authors.

At the same time, it was widely acknowledged by experts that although EVs have a higher capital cost, they also would represent economic savings when viewed from a total cost of ownership (TCO) calculation. But experts believed consumers would not approach the economics of car ownership in this manner, instead, the price tag would dominate decision-making. R14 notes that this is not an uncommon problem in energy, casting EVs as a typical energy efficiency problem:

> *"Then there is the whole upfront cost problem…that's a classic problem in energy efficiency policies."*

Many experts acknowledged that even if EVs do have a better TCO than ICEVs, this simply would not resonate with the manner in which consumers acted. As R33 notes, people tend to think in terms of capital cost, not total cost of ownership:

> *"And another is price, they are still quite costly. You have to pay a lot more to get an electric vehicle. If it is more expensive, it is more difficult. People don't think of it in total cost of ownership."*

Similarly, R54 adds that it does not matter what a TCO would say because it is incompatible with how consumer conceptualize the economics of vehicle ownership:

> *"Well, I'm sorry, you've heard this dozens of times before, but the price; it's expensive. And it doesn't matter that it's very much cheaper when you drive it, because that's not how people reason."*

Although TCO was widely recognized as a potential benefit, many experts connected the economic aspects of EVs to a type of mental barrier. Compounding the problem, consumer's aversion to TCO is that, as R53 says, consumers will treat EVs and their higher price with increased scepticism because of the emotional connection to ICEVs:

> *"You need to have a reduction in price to have a lot of sales, but you shouldn't underestimate these social issues. Because cars are a lot of emotional things."*

Likewise, R105 suspended their focus on implementing EV, since it wasn't possible for consumer to move past the price tag:

> *"Right now, we've put it a bit on hold, the electrification of private transportation, because the cars are still more expensive and as long as they're more expensive, we cannot convince people to change."*

And even though many other countries viewed Norway as having resolved the price barrier through their plethora of incentives, 11 experts in Norway still maintained price was the primary barrier that the transition to EVs is facing. For example, R171 noted that even in Norway, not everyone can afford the higher-end Tesla:

> *"You need cheaper cars and of course not everybody can afford a Tesla. So you need cheaper small cars, which you can use for small and low income families."*

While it is clear that price is in some ways connected to the consumer knowledge aspects of the nexus (discussed further below), price and range were also correlated with each other. For instance, R50 noted that price was preventing them from buying a car that sufficed their range demand:

> *"Yea, the combination of price and range…when I can afford a Tesla, I buy one."*

The idea that price and range was a trade-off between each other was common. R84 added that there needed to be an appropriate concession between the two:

> *"The biggest challenge is still price and battery. It's the trade-off of having the price going down while you want the battery capacity to go up. Finding the compromise between those two."*

The connection between price and range was the strongest component of the nexus, and many experts listed both price and range, though in contrasting orders. The nexus of range and price also connected to other barriers, such as long charging time, which R127 also demonstrates:

> *"The biggest barrier about electric vehicles is twofold. First of all, I'm not sure which is the first and which the second, probably the price of the cars, that's the thing. And the second or the first one, is the range, how far away you can go with your car. And that is related also to the question about how fast you can charge the car."*

Finally, it is worth mentioning that price also affects the electrification of public transport. When asked about the main barrier for public EVs, R151 said the barrier was the price of not only the bus, but also the related infrastructure:

> *"Money. It is the main barrier, because it's not just buses which are also rather expensive, but it's also the infrastructure that you have to build."*

At the same time, similar to the range barrier, many experts also characterized price not to be a barrier. As shown in Figure 2, 12.3% of experts believed that price either is already not a barrier or soon would not be a barrier. Unlike range, however, the vast majority of these experts believed that the price would still require some time before it was no longer a barrier. Indeed, R35 believed that the price of EVs would fall to such a degree within the next five years that government should not focus on subsidies, but rather prepare other aspects of the electrification of personal transport, like charging infrastructure:

> *"So I think if the government decides now to do something, in five years' time, when they actually implement it, it will be too late. And electric vehicles will be cheap enough anyway, and what we really need is charging for them."*

Of the few experts who explicitly stated that price was not a barrier, many of them connected it to consumer knowledge and TCO. For example, even in Denmark, where the registration tax system had recently started taxing EVs by 40% (Lambert 2017), R77 believed that the price barrier was overstated and actually just a misinformation barrier:

> *"The real challenge may be not so much the price, but that it has been talked about so much. [This has a] negative effect. People believe that electric vehicles are extremely expensive now, which they aren't (although they're still more expensive). So it has had a really great impact that there has been so much negative talking about it, unfortunately."*

Indeed while only 2% of experts explicitly stated that price was not a current barrier, many of the other experts did connect consumer awareness and knowledge to how price is viewed as a challenge. Thus, price is connected both to the range and consumer knowledge barriers.

3.1.3.3 Public charging infrastructure

The third aspect of the nexus and third most commonly discussed barrier was the need for public charging infrastructure. Compared to the first two barriers there is a slight drop-off in the extent of experts discussing public charging infrastructure, comprising just under half of the experts. Unsurprisingly, public charging was framed as a consequence of the long distances that were common in much of the Nordics. R5 noted that only Tesla had built the infrastructure in the desolate lands in between cities in the Nordics:

> *"The biggest challenge about electric vehicles is that the charging station are so few at the moment. So the infrastructure is just at the starting point. So, from here to drive to the north side of the country, it's only Tesla [charging stations]. You don't have anything along the way, unless you have your charging station with you and can go to the next farm and get to charge it for the next two hours or something."*

R224 also described the difficulty of providing sufficient charging opportunities in the long distances within Norway that do not have any people:

> *"It's a problem with infrastructure that we are spread out in northern Norway so much that is hard to expect the charging stations to be all the way to, let's say, Finmark. That's 7 hours away. I could get to the ferry, the first ferry, but I would pretty much stop after that because I don't think there are any chargers after that. So I need to charge at least 3 times on the road. And that's not how we are used to driving. There are long distances."*

In Norway, where EV integration is far ahead of the rest of the Nordics, charging infrastructure was still a challenge, though it was framed as more of a challenge to extend the existing network to meet increasing demand. For example, R175 described a story they had heard about their colleague traveling to their summertime cottage:

> *"So yes, that's when we will have the charging network constrains. Queues at super chargers today. A colleague of mine told me that 5 EVs were waiting in line for one charger at some point, a few hours up in the mountain… So if you are the 5th or 6th car*

> *coming there and each car is going to use, 30 min, you're 2-3 hours stuck there, and he could observe that people were frustratingly waiting."*

Despite many viewed the challenge as simply not having enough chargers available to the public, the solution was not so straightforward. While a simple solution would be to merely build more chargers, many of the experts lamented that the demand for charging was not sufficient enough to encourage this development, resulting in a type of a "chicken and the egg" problem. This barrier was common across all the Nordics. For example, R126 described the chicken and egg barrier in Finland:

> *"So these are the two things and it's a bit chicken and egg problem that everybody talks about. Ideally the cars would be affordable because that would drive the necessity to develop infrastructure and then more private companies would be interested in developing infrastructure."*

Norway, where presumably the EV demand would already be present, was not immune from the chicken and egg classification. R218 in Norway still described the chicken and egg impeding the development of charging infrastructure:

> *"But of course, there is a challenge with infrastructure. And this chicken and egg problem, of course, people want to go wherever they want, and they want to be sure that there is charging infrastructure available."*

Finally, the chicken and egg challenge is further complicated by the fact that much of EV charging will occur at home, not at the public chargers, as R39 describes:

> *"It's like the hen and egg, which comes first. You cannot have electric vehicles without grid infrastructure, or you cannot have the infrastructure, but you do not use it. They go hand in hand. Then, they find out that 80% of the charging is at home. So, it is not easy to build infrastructures."*

Indeed the public charging infrastructure challenge more generally was commonly connected to other parts of the nexus proposed in this paper. For example, R165 characterized price as the primary barrier, but lack of charging infrastructure is the secondary barrier, and also might pose life-threatening danger to EV drivers in Finland:

> *"The price is number one and then probably the charging network is not yet developed to every city, so that's also something that you need to consider, especially driving during winter. You do not want to go to that area where you know you are not able to charge and then you are risking your life basically if you are stopped in the forest."*

In fact, many of the experts explicitly connected all three technical aspects of the nexus. R58 listed all three as interrelated, particularly range and infrastructure:

> *"Price and range, and infrastructure. And that is in some way connected with the range, because people think that they drive much longer every day than they really do. And then they think 'my car will run out of electricity and I will be stopped, and there is no infrastructure, so where can I load, where can I charge my car.'"*

R93 also connected all three in a nexus, but clarified that charging was the third barrier:

> *"The price, the range, the limited range that's the biggest two barriers, from the customer as well as the non-customers. And then the charging time also comes, but that's the third biggest because you can get around that. You can plan that. It will give you some limitations but you can get around it."*

Beyond the nexus, public charging was also connected to other less common barriers. As an example, R204 saw fast public charging as a way to get around the barrier of apartment charging barriers (discussed more below), which Norway was facing:

> *"The charging network of course. Fast charging network. If all new car customers should buy electric cars you have to have a much better network than today. It must be fast charging, if you live in areas in Oslo city, you don't have to possibility to charge at home, for many people, then you have to have other choices for fast charging. And today we are not good enough."*

On the other hand, as with the previous two barriers of the nexus, there was also a sizeable amount of experts characterizing public charging as not a barrier. However, unlike price and range, which were most commonly designated as barriers that would dissipate in the very near future, it was much more common for the experts to characterize public charging as currently and explicitly not a barrier. As shown in Figure 11, 12% of experts characterize public charging as not a barrier, and over 80% of those classified public charging as *already* not a barrier, meaning that it did not need time to for the barrier to be assuaged. Most of the experts saying public charging is not a barrier were generally split into two categories; either the current amount of public infrastructure was sufficient, or that public charging was not necessary and was instead a type of mental barrier due to lack of knowledge or experience (Smart & Salisbury 2015). The idea that current public charging infrastructure was sufficient was particularly associated with Denmark, as R73 notes:

> *"We have a lot of infrastructure in Denmark, charging points. We have, per each vehicle, electric vehicle we have, I think we have the highest number of charging points. So that's not a barrier."*

One reason that Denmark was particularly sufficient in its public charging was that it had the remnants of Better Place, a company that sought to resolve charging networks, as R86 observes:

> *"It is a bit different from anywhere else. Denmark has the best infrastructure in the world, and it has been done very much on a private base. The reason that has happened is because the company called Better Place, they had a strategy saying okay, just do it. They invested a lot of money and went bankrupt. They had the charge stations that were dismantled, but they also had a lot of charge spots. Those were suddenly for sale and the energy company E.ON bought the system."*

Outside of Denmark, the discussion tended to focus on the mental aspects of public charging networks, or that consumers mistakenly believe that they needed public charging to a much greater degree than they did in actuality. As R11 summarizes, infrastructure demand was a result of mental barriers:

> *"Infrastructure wise, I don't believe it's the barrier. Mentally it is the barrier, because people think they need to charge everywhere, they think they need posts everywhere."*

Similarly, building on personal experience, R216 didn't understand the need for public charging, given the infrequency of which public charging was necessary:

> *"I don't understand that really. I have had my EV for one year and I think I've fast charged my car two times. And I am driving 15,000 kilometres on a yearly basis."*

Thus, the public charging barrier may be borne out of consumer inexperience with EVs and undervaluing charging that may occur at home or work. Lastly, though many experts believed public charging was already not a barrier, only five experts discussed public charging in context of soon not being a barrier. Most of these were either in context of the buildout constraints of developing the entire charging network, or in tandem with new EV models increasing range.

3.1.3.4 Consumer knowledge and experience

To round out the top four most common barriers and complete the proposed nexus, the next most discussed barrier focused on the consumer: either their lack of knowledge or experience, or other mental barriers. And unlike other aspects of the nexus (e.g., public charging infrastructure, which was commonly described as secondary to other barriers) consumer knowledge was more prominent in the discussion of barriers. To many experts, consumer knowledge was the primary barrier to EVs, as R104 who put it succinctly:

> *"The biggest barrier in Denmark is the mental barrier."*

Correspondingly, for R66, consumer information and experience is the number one priority for transport policymakers working on EVs:

> *"I'd say, the number one barrier that transport people should focus on, is perception. There is still a view that it's all really nice, but not for me. So, we need to work with information and customer acceptance and testing opportunities."*

Likewise, lack of EV knowledge allowed myths to continue to persist in Norway, in spite of their strong support of EVs, as R177 of Norway documents:

> *"And we see that there is a huge need for good information, correct information. There are a lot of myths when it comes to the batteries: people think they are toxic, people think they are, you know, going to break easily, that you need to change batteries every four years…. There are a lot of misconceptions related to EVs basically."*

However, more importantly, and as hinted in the discussion above of the nexus between range-price-public charging, experts commonly connected the nexus to consumer knowledge and experience, claiming these technical barriers were actually rooted in mental barriers. Nearly all of the discussion of consumer knowledge and experience focused on the three technical aforementioned aspects of the nexus. First, for many experts, range was not actually a technical barrier, but rather was a knowledge and experience barrier, given that EVs could suffice the vast majority of the average trips an average resident in the Nordic countries would take (Liu et al. 2015). As a result, R93 pointed out that this mismatch between technical sufficiency of range and subsequent range anxiety was a result of consumer ignorance:

> *"And people, that's another, people don't know the possibility of doing the charging at home. People don't know that 92% of all trips can be done by the range of a normal EV. So the car is also a symbol for freedom in our part of the world. And then there is a knowledge gap."*

The idea that EVs could meet over 90% of daily driving demands was often brought up by experts when discussing the connection between range and mental barrier aspects of the nexus. Adding to this, R31 also connected to lack of knowledge to range as well as winter weather implications on range:

> *"So, I think the important thing is people's mentality. Because 95% of all the distances people are driving per day in Europe, not just the Swedes or Norwegian or Danish, is 50 kilometres a day. Any electrical car that existed from 2009 and forward has made that. So, it's not that big of a problem even in the Scandinavian winter climate."*

Finally, the mental barriers regarding range may be difficult to resolve. As R45 recognized in their experiment of giving people an EV to use, consumers still saw range as barrier despite experiencing the EV sufficing their daily travel demands:

> *"Yea, there could be prejudisim about it. It could also be a barrier that is much more connected to experience: of thinking that you need more range than you actually do. Even in our experiment, [the participants] see range as a limit [even though] they manage with the range they get – we had an e-Golf, which practically got around a hundred and thirty kilometers, even if it's stated as more. They never had any problem, they managed all the trips, but they still wanted more range."*

Moving onto the second aspect of the nexus, the price barrier was also seen as a result of consumer mental barriers, typically focusing on lack of consumer knowledge. R25 noted that consumers in Iceland tended not think rationally when it came to realizing economic savings from a TCO perspective:

> *"It's hard to say maybe, I'm going to say it though [I'm] insulting the entire nation. We are not the smartest consumers, we just go for things. So sometimes it's hard to introduce things that have a payback time."*

This is not an issue specific to Iceland or the Nordics, indeed, it is typical for consumers to highly discount future savings (Allcott & Wozny 2014; Hausman 1979). Exacerbating this issue, some experts believed that because consumers were generally distrustful of EVs, consumer would not even believe the idea that the TCO of EVs is lower (much less discount properly), as R32 describes:

> *"The electric motor is more economic to drive itself. I drive an electric car since a year and a half, and I have never had so cheap a car. But it's hard to explain to people. They don't believe in it yet."*

On the other hand, while experts noted various issues with consumer awareness and the economics of EVs, other experts believed that price was not very influential on consumer behaviour. As R89 illustrates, EV deployment might not depend on consumers understanding TCO in the face of a higher price, but rather the fashionability of EVs:

> *"So it's not within the money, the money is not the problem here, I think. [Because} even when it comes down to electrical cars, it's very much down to fashion and perception. And now the minute it gets fashionable to drive an electrical car [snaps fingers], it can cost a lot."*

Regardless of how relevant price and TCO are to an EV implementation, it is clear that there are to some extent mental barriers that affect consumers' willingness to purchase EVs or even their willingness to consider EVs.

Thirdly, experts also connected consumer knowledge and experience to the public charging infrastructure barrier. In this case, most of the experts attributed consumer ignorance to the perception that public charging infrastructure was an impediment, often connecting the technical sufficiency of EV range and availability of home charging, as R29 describes:

> *"But you know, 95% of all the EVs owners in Iceland, they charge at home only. 95% of all the charging, they do at home. But it's a mental state, you know, you need to see [public chargers] everywhere, or otherwise I can't buy a car. "*

As a result, many experts believed that the focus should be on developing home and work charging instead of high power public charging. For example, R45 believed that home and work charging infrastructure was more important, but recognized people still felt they needed public charging as "insurance":

> *"I think when it comes to charging infrastructure the two most important places are the homes and the work place. And once you have those, you cover quite a lot. But at the same time, people, you know when you talk about this in a lot of interviews with people, they want more charging infrastructure. But then the question is how much should they actually [need]. It's like charging is kind of an insurance. You feel that you want it, but you're probably not going to use it that much."*

Moving beyond the nexus, consumer knowledge also affected how consumers viewed the benefits of EVs. Indeed, R52 blamed the consumer skepticism and lack of knowledge of modern EVs on the first EVs that were ridiculed as inadequate:

> *"And people have been skeptical to electric cars, as just a couple of years ago the electric cars were quite primitive. I mean, our first cars were these Norwegian Thinks. A brand that ultimately disappeared. And they are like Donald Duck cars, plastic things. It's like a joke. So, that's the mental view people have been having."*

As a result, many experts believe that experience with modern EVs is vital to educating people of the benefits that EVs can offer. Such experience can help shatter preconceived notions of what consumers believe an EV is. The surprising benefits of EVs leaves consumers with what R33 calls the "EV smile":

> *"People talk about the EV smile that happens when you have driven an electric vehicle for the first time and come out with a smile on your face. Everyone talks about that. In the EV world, it's something you are aware of, and that's what happens."*

While experience is key to educating consumers about the benefits of EVs and both information and education may be necessary to properly characterize the technical aspects of the nexus, it was noted that mental barriers may be the most difficult to resolve. As a result, R98 believed a reduction of consumer's mental barriers will likely lag behind technical improvements to the range-price-charging nexus:

> *"I think the technology will run faster than the mentality of people will change. So, I think the solution will be that the batteries are actually getting better. Even though you are completely right. But I think it takes a shorter time to develop the technology than it takes to change the mind of people."*

3.1.3.5 Other prominent barriers

Moving beyond the four most frequent barriers, each of which were discussed by at least 40% of the experts, there were seven additional barriers that were discussed by at least 10% of the experts: apartment charging, lack of consumer incentives, lack of car models, grid integration, winter weather, lack of political will, and long charging time.

Charging infrastructure for townhouses and apartment complexes was discussed by just over 20% of the experts. Unlike the other more technical aspects of the nexus discussed above, there was limited connection between apartment charging infrastructure and mental barriers. Similarly, less than 15% of experts discussed apartment charging in the context of EV's range, making it far less connected to the nexus than most other barriers. Many experts believed that resolving apartment charging would be very difficult as it relies on other stakeholders, as R35 notes:

> *"The biggest barriers are people living in apartments. If you own your own house, you have no problem at all, but if you live in an apartment, you need to get the house-owner to install the charging station. And that has been extremely difficult."*

Worse yet, apartment charging is not a niche problem, as R69 noted that a large subset of the Swedish population is living in apartments:

> *"I think one thing that we didn't talk about concerning the infrastructure, in Sweden, it's fifty percent of people live in apartment buildings, they don't necessarily have access to their own parking spot, and I think that's something we have to address."*

Finally, there were social aspects of apartment charging. R136 discussed that apartment charging also raises questions of equity and could even lead to fights:

> *"I have heard rumors that there are actually big fights, because somebody has an EV and then the other ones of course say - we are jealous people here in Finland – 'no you cannot charge your vehicle here because there are no rules for how to do it, we don't want to pay for your charging'."*

While apartment charging was not as widely discussed as the four central barriers, there was also not as much hope that it would be resolved within a short time frame, like range and price could be. And unlike the other three technical barriers discussed, it is unlikely that better information and education of consumers would reduce the perception of this impediment. For these reasons, apartment charging might be the most persistent barrier in the near future of EVs.

For many of the remaining technical challenges, range permeated throughout. For example, R64 described their personal challenges using their company's EV both as a result of the long charging time and the lack of range:

> *"Sometimes when we have customer visits that might be 150 kilometres away you wouldn't take that car. So, there are limitations as well. Even if we know there is a charging station halfway, we still won't take it, because that is too time consuming. Time is always an issue."*

Similarly, winter weather was frequently discussed in the context of its impact on range, with half of the experts explicitly connecting winter weather to range. For example, R1 noted that range was particularly a challenge in Iceland when temperatures reached below zero and reduced the range by more than 50%:

> *"But then still we have a few days that it is minus five to minus ten, but that's only 10 days of the years or something like that, and when it happens the EVs that are supposed to be 250 kilometres go 150 or 100. So that's an issue. "*

Likewise, in Finland, R151 connected range and public charging infrastructure to how winter limits range for long holiday car trips:

> *"The range of the electric vehicles is not enough, especially in the winter time, if you want to go for a holiday in Lapland. You don't have charging stations and then it maybe minus twenty, thirty, forty even, so it's a bit challenging."*

Next, it was common for experts to suggest that the biggest barrier was the lack of government action to provide consumers with incentives to purchase EVs Lack of consumer incentives was suggested as a barrier by nearly 20% of experts, while lack of political will was submitted by 12%. Of the 45 experts who discussed the lack of consumer incentives as the central barrier to EV adoption, about 60% were from Denmark. The next most was Finland, with 12 experts discussing lack of consumer incentives as a barrier. The remaining 6 experts were split into Iceland, Sweden and Norway. While the magnitude varied across the Nordics, nearly all experts who discussed lack of consumer incentives focused on the lack of subsidies to reduce prices either by reducing registration taxes or annual car taxes, particularly outside of Norway. Only 2 out of the 45 experts connected the lack of consumer incentives to the secondary benefits, i.e., free parking, tolls, driving in the bus lane, etc., implying that price was perceived as much more important dimension than other consumer incentives.

It was a very similar story regarding the lack of political will, which was likewise very regionally disparate. By far the most experts, again nearly 60% of the 28 total experts, were from Denmark, who had recently removed the exemption to EVs, increasing the registration tax to 40%. Correspondingly, practically all the discussion in Denmark focused on the complexities of the registration tax scheme, and the political risk that increasing ICEV costs would entail to subsidize EVs. Finland comprised the second most common country, with 7 experts claiming that the lack of political will was a major barrier to EVs. The government inaction in Finland was attributed to the powerful biofuel industry, implications that the government did not want to favour EVs over biofuels, and as well as general EV inexperience, particularly on a city level. The remaining 5 experts were from Iceland, Sweden and Norway.

Finally, the remaining barrier was the impact of charging on the grid. Though this issue returned in all the Nordics, it was most commonly discussed in Norway. Nearly all the discussion was focused on distribution networks. R213 describes that the challenge isn't the total amount of energy EV charging requires, which was generally seen as minimal, but rather providing the power through weak distribution networks:

> *"We have enough electricity, that is no problem. But you can have, you know, problems with the distribution network and such."*

Interestingly, the grid integration issue was split, as for every two experts who believed it was a barrier, there was one expert who believed it was *explicitly not a barrier*, see Figure 11. This remained true across the countries, as there was a near-mirrored distribution across the Nordics for both those experts who said it and those said it was not a barrier.

Beyond these common barriers there was still a remarkable list of 42 other challenges discussed. Many of the remaining barriers, though not widely discussed, focused on the techno-economic aspects of EVs, like various issues related to batteries (lifetime, recycling, production) or challenging business models and electricity taxation. It is worth to note that, curiously, 9 experts believed that there were no explicit barriers to EVs, and an additional 10 believed that the only barrier was time. But of those 19, only 8 were not from Norway. Stated another way, of those who did not believe there to be a substantial barrier to electrification, ~60% were in Norway, where the government has taken substantial steps to address the barriers to EVs.

3.1.4. Conclusion & Policy Implications

Indubitably, even in the Nordic region EVs face a wide variety of barriers, though much of the focus both in the literature and by the experts interviewed emphasizes range, price, charging infrastructure, and psychological factors. It is undeniable that there are true techno-economic aspects behind the nexus of range-price-charging; the range is certainly less than an ICEV, the price tends to be higher looking only at the sticker, and there are far more gas stations than public charging infrastructure. However, a closer look at this nexus will reveal that these barriers proposed by the experts we interviewed are more deeply rooted in sociotechnical dimensions such as consumer knowledge and experience.

For instance, range is technically sufficient for well over 90% of trips taken by Nordic drivers (Liu et al. 2015; Pearre et al. 2011b), but consumer acceptance of transitioning to a vehicle that is incapable of providing *all* trips remains a substantial barrier, regardless of potential solutions or the infrequency. Similarly, public charging, which is very rarely used in day-to-day use of EVs (Smart & Salisbury 2015), correlates to consumers perceptions of range. And for price, it is clear that consumers focus on capital cost of vehicles rather than on the total cost of ownership calculations, which favours ICEVs despite not being the least-costly option in the medium to long term. A key aspect, is the irrationality of private individuals over discount rates (Allcott & Wozny 2014; Hausman 1979), which could play a central role in the transition to electrification. Consumer perception and understanding of personal vehicles are at the core for reducing the impact of the nexus of technical barriers moving forward, and thus foster increasing deployment of electric vehicles internationally. Future research should not only recognize these inherent links between the technical and non-technical elements, but also work to understand the dynamics of interconnectivity amongst the barriers of the nexus.

While the techno-economic aspects of the price-range-charging nexus are expected to decrease mostly in the near future, the prevalence of mental barriers may imply that there will be a lag between the diminution of technical barriers and the time when consumers have the knowledge and experience requisite to choose EVs as their primary or solely mobility option. Given the nexus of barriers, the implication for policy making is that EV policy should not focus on a single barrier, but rather use a set of tools to address the nexus to resolve the social roots of the various technical challenges. Thus policymakers should carefully consider any policy that addresses this nexus in the context of the consumer knowledge and experience barriers. As an example, many experts viewed developing a comprehensive charging network as very expensive – this may be especially true if an alternative is a low-cost consumer information campaign realizing that a comprehensive public charging network is not as necessary as it is commonly believed (Smart & Salisbury 2015). Indeed, giving information and experience to consumers may be a cheaper alternative while also being more effective than resolving to a techno-economic policy approach. Similarly, the proposed nexus does not only cover users of private vehicles, but also fleet owners and public transportation operators. As such, fleets and public transportation electrification policy should also acknowledge the interconnected nature of the EV barriers nexus.

Finally, though our work implies that consumer knowledge and experience lie at the roots of many of the perceived technical barriers, there are some barriers that appear to be mainly technical, like apartment charging solutions. However, apartment charging too faces social resistance by way of sceptical housing authorities. Additionally, while numerous experts agree that the technical aspects of the nexus (range-price-charging) will be resolved within a short time frame, such solutions are not readily apparent for apartment charging. Thus, to the extent policymakers wish to invest in charging infrastructure, our results imply that home and work charging, particularly for those living in apartment complexes, should be favoured over public charging networks.

Moving forward, this paper calls for further research, policy development and decision-making to recognize the dynamics and relationships among the plethora of barriers that electric vehicles face. The temporal aspect of some of these barriers should be studied to understand how the near-future reductions of barriers will impact the adoption rate of EVs. Also, future research should certainly be undertaken in order to understand how the nexus, as described by experts, compares and contrasts to a consumer perspective. We have demonstrated that EV barriers are not solely based on either technical or non-technical elements, nor do they operate in isolation. As the quest for decarbonizing transportation continues, and electric vehicle technology becomes more prominent, policymakers and researchers should continue to explore the interrelated (and constantly evolving) nature of this nexus.

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3.2 Beyond Emissions and Economics: Rethinking the co-benefits of Nordic Electric Vehicles (EVs) and Vehicle-To-Grid (V2G)

The fourth article presented in this dissertation (and second article for this theme) considers that, despite the perceived advantages of cost-savings and carbon reductions, such technologies have faced various barriers that have prevented wide-scale adoption. While much literature has carefully investigated the techno-economics dimensions to electric mobility, we ask: what are the full set of benefits that EVs and V2G offer? To provide an answer, the authors conducted 227 semi-structured interviews with transportation and electricity experts from over 200 institutions across the Nordic region. Results show that there is an extensive range of benefits for both EVs and V2G, with experts suggesting 29 and 25 categories of benefits for EVs and V2G, respectively. Though the experts covered the obvious benefits of economic savings, emissions, and renewable energy integration, several other novel benefits were identified. The second and third most common discussed EV benefit was noise reduction and better performance, which are typically not widely discussed. Similarly, we found that V2G benefits covered topics like vehicle-to-home and solar integration, as well as more novel benefits, like vehicle-to-telescope and emergency power backup. The article concludes with a discussion of future research and benefits in the context of energy research and analysis.

3.2.1. Introduction

Electric vehicles (EVs) and vehicle-to-grid (V2G) are often regarded as a key aspect of the sociotechnical transition to decarbonize transportation. In order to optimize this transition, it is essential for policymakers to understand the entirety of the benefits EVs and V2G may offer, as well as the challenges they would pose. A variety of previous papers have explored the potential benefits of EVs and V2G could bring to society, such as climate change mitigation, local health emissions, and lower cost of ownership, though they often only discuss these benefits in the context of the barriers EVs and V2G also face (Sovacool et al. 2017; Sovacool & Hirsh 2009; Egbue & Long 2012). Other papers have focused on characterizing a single benefit, such as the quantification of emissions benefits EVs and V2G offer (Buekers et al. 2014; Archsmith et al. 2015; Sioshansi & Denholm 2009) or reducing the heat island effect (Li et al. 2015). No previous work has sought solely to comprehensively describe the full range of co-benefits of EVs and V2G.

For example, papers that compare the costs and benefits of EVs and V2G focus exclusively on how emissions and economics impact the cost-effectiveness of EVs in context of alternative transport options (Carlsson & Johansson-Stenman 2003; Lemoine et al. 2008; Villar et al. 2013; Noel & McCormack 2014). While some may recognize there are other benefits EVs could offer, such as noise, they are not included in their analysis, due to some benefits being admittedly difficult to monetize and include in comparisons (Carlsson & Johansson-Stenman 2003). Similarly, the benefits of V2G tend to focus on the economic and emissions benefits of services provided to the grid (Lopes et al. 2009; Sovacool & Hirsh 2009; Noel & McCormack 2014). Likewise, EVs and V2G are often included in analyses of large-scale renewable integration, but are also only evaluated on their economic and emission costs and benefits (Jacobson & Delucchi 2011; Budischak et al. 2013; Noel et al. 2017). Nonetheless, there may be more benefits to EVs and V2G beyond these two, and if not included, these papers may unintentionally suggest suboptimal transport and decarbonization policy. We endeavor to describe the full context of benefits of EVs and V2G beyond costs and carbon.

This paper aims to explore the benefits of EVs and V2G past the current narrow techno-economic focus in the literature by characterizing the entirety of the benefits these technologies could offer. To describe the benefits, the authors conducted 227 semi-structured interviews with 257 participants from over 200 institutions across the five Nordic countries. Given the electrical nature of EVs and V2G, those interviewed were selected to represent the diverse array of stakeholders involved with the transportation and power systems, technology, policy and practice. Selected experts were from national government ministries, agencies, and departments; local government ministries, agencies, and departments; regulatory authorities and bodies; universities and research institutes; power transmission, distribution and supply utilities; automobile manufacturers and car dealerships; private sector companies; and industry groups and civil society organizations.

We find that the experts presented a diversity of benefits for both EVs and V2G, advancing different benefits of each, 29 and 25 respectively. We find that the experts discussed the obvious benefits of emissions and economics for both EVs and V2G, as well as several novel benefits not included in the aforementioned EV cost-benefit analyses. The benefits tended to focus more on an individual level, as opposed to societal benefits, such as noise and advantageous performance for EVs, and V2G integration to homes with solar panel. We present the full results below, and then conclude with a discussion of the implications for future EV research and transport policy.

3.2.2. Materials & Methods

To explore the benefits surrounding electric mobility, namely electric vehicles and vehicle-to-grid technology, the authors relied primarily on original data collected through semi-structured research interviews. This methodology was applied on a regional context taking the five Nordic countries as place of study, since it is recognized that these countries have traditionally had aggressive push of climate, energy and transport policy agendas emerging as leading nations in electric vehicle uptake (Norway), or pioneers of wind energy (Denmark), or geothermal energy (Iceland)(IEA 2016).

The implementation of *semi-structured interviews* allows the authors to have guidance and flexibility, by asking a set of fixed questions to then, create a conversational channel of information-gathering, allowing space for spontaneous responses that add depth and in some instances unforeseen narratives to the research (Harrell & Bradley 2009). This semi-structured form of interviewing is suitable when the objective of the research is to understand complex elements and their intersection with perceptions, beliefs, and values (Yin 2003). Lastly, the authors selected this research method as it allowed for novel and up-to-date data (at the time of the interview) which was not available in other formats, since official documents can take months or even years to be published.

The authors conducted 227 semi-structured interviews with 257 participants from over 200 institutions across the five countries of Denmark, Finland, Iceland, Norway and Sweden from September 2016 to May 2017 (See appendix 6.3 for an overview). Those interviewed were selected to represent the diverse array of stakeholders involved with transport technology, policy and practice, and included members of:

- National government ministries, agencies, and departments including the Ministry of Industries & Innovation (Iceland), Ministry of Environment and Energy (Sweden), Ministry of Finance (Finland), and Ministry of Taxation (Denmark):
- Local government ministries, agencies, and departments including the Akureyri Municipality (Iceland), City of Stockholm (Sweden), Aarhus Kommune (Denmark), City of Tampere (Finland), City of Oslo (Norway), and Trondheim Kommune (Norway);
- Regulatory authorities and bodies including the National Energy Authority (Iceland), Danish Transport Authority, Icelandic Transport Authority, Helsinki Regional Transport Authority (Finland) and Trafi (Finland);
- Universities and research institutes including the University of Iceland, Swedish Environmental Institute, DTU (Denmark), Aalborg University (Denmark), VTT Technical Research Centre (Finland), NTNU (Norway), and the Arctic University of Norway;
- Electricty industry players such as ON Energy (Iceland), E.ON (Sweden), Vattenfall (Sweden), Energinet (Denmark), DONG (Denmark), Fingrid (Finland), Elenia (Finland) and Statnett (Norway);
- Automobile manufacturers and dealerships including the BMW Group (Norway), Volvo (Sweden), Nissan Nordic (Finland), Volkswagen (Norway), and Renault (Denmark);
- Private sector companies including Siemens Mobility (Denmark), Nuvve (Denmark), Fortrum (Finland), Virta (Finland), Clever (Sweden), Nordpool, (Sweden), Norske Hydrogen (Norway), Microsoft (Norway) and Schneider Electric (Norway);
- Industry groups and civil society organizations such as Danske Elbil Alliance (Denmark), Finnish Petroleum and Biofuels Association, Tesla Club (Finland), Power Circle (Sweden) and the Norwegian Electric Vehicle Association.

As such, we targeted respondents with different backgrounds and from dissimilar sectors to capture a diversity of perspectives within the sample. Such techniques have been shown to increase the validity of research in the fields of critical stakeholder analysis, political science, statistics, energy studies, and public health (Aligica 2006; Mushove & Vogel 2005; Beamer 2002; Godambe 1982; Flowers et al. 2003; Topp et al. 2004) . Participation was voluntary with no compensation.

Interviews lasted generally between thirty and ninety minutes in their duration, and participants were asked one main question: “What are the full set of benefits that electric vehicles and vehicle-to-grid offer?” and the following context in the interview was developed according to the background of each respondent. Other questions, such as the barriers that EVs and V2G face, were also asked, but these results are reported in separate papers. In the study, participants were not prompted for responses, talked on a personal level, and were permitted to answer as long or as detailed as they wished. This approach is sometimes termed *ethnographic* as it involves taking what the participants and experts said at face value, we did not correct them, critique them, suggest answers, or view our own values and attitudes as superior. This technique requires researchers to acknowledge that their position is just as valid of those they are interviewing, and implies a special responsibility to look at local events and cases within their own frames of reference (Atkinson 1988; Martello & Jasanoff 2004). Each interview was recorded and then fully transcribed and analysed. Each participant was also given a unique respondent number (which we refer to whenever presenting interview data).

3.2.3. Results and Discussion

3.2.3.1. EV Benefits

In total, our data collection and analysis resulted in 29 different categories of the benefits that the experts identified, with Figure 12 summarising the frequency of each benefit. Here we discuss, the five most commonly discussed EV benefits (emissions, noise, performance, economic savings, and renewable energy integration), and the summarize the remaining benefits.

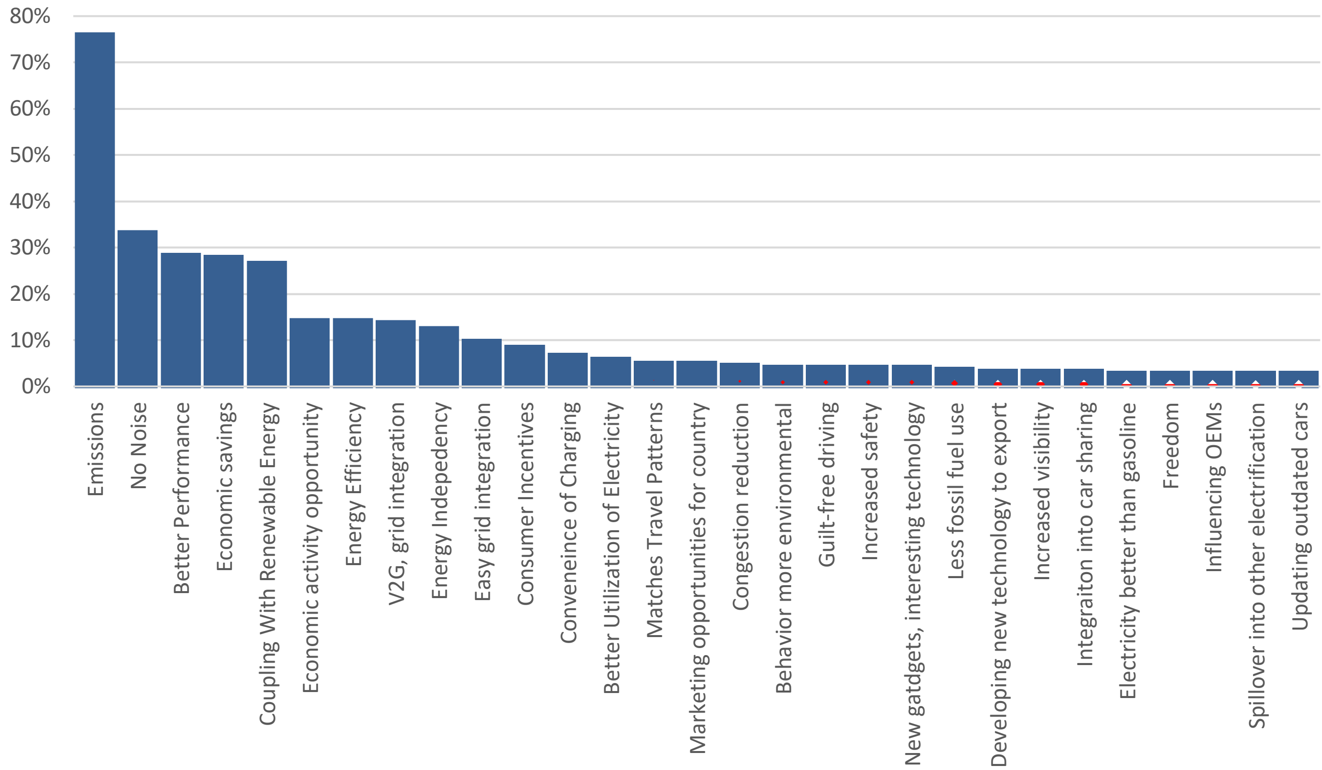

Figure 12. Co-Benefits of Electric Vehicles Identified by Interview. Note: constructed by authors.

While there was a great variety of the types of benefits discussed, by far the most dominant benefit of electric vehicles was the impact they would have on reducing emissions. Of the 227 interviews, 167 characterized the benefits of EVs in terms of their environmental benefits, representing over 73% of the interviews. Of those who mentioned emissions, 99 interviews explicitly tie this benefit to the carbon emission reductions of EVs as compared to ICEVs, and while 94 interviews also explicitly mention the impacts EVs would have on decreasing local health emissions, such as NO_X and particle matter. On their own, carbon and local emissions would each be more discussed by the experts than the second most commonly discussed topic, showing that emissions dominated the discussion of EV benefits. In fact, the carbon benefits of EVs had become almost too obvious –as R232 put it:

"*Well again the whole picture is the decarbonization…We didn't mention it because it's so obvious*."

Indeed, though emissions are already the most commonly discussed, it perhaps could have even been *more* discussed had experts not simply assumed these benefits were too obvious to warrant further discussion. In many cases, it seemed like the experts were merely checking off the box of emissions before moving onto more novel benefits of EVs.

Surprisingly, the second most common benefit discussed by the experts was the noise reduction that electrification can offer. The lack of noise was characterized for the individual user (e.g. the driver will enjoy the quietness and the simplicity of an EV), the non-users (i.e. cyclists or pedestrians), as well as from an urban planning perspective. Many viewed noise emissions from ICE vehicles as a great cost, as it reduces living conditions for those living near major roads within the city, and thus EVs could increase both housing prices and improve local health. As an example, in Denmark R120 told us that noise is considered the new pollutant that EVs could help solve:

> *"We see noise as being the new pollutant, which is not really tracked but definitely has a big effect, we see five hundred, six hundred people die prematurely as a direct cause of too high of sound level all over the day and night in Copenhagen."*

This was not an issue specific to Denmark, but was present across the Nordic region, as R208 added that Oslo city centre also faces similar challenges that electrification could likewise solve:

> *"But also it has a significant contribution to noise, and noise levels inner city is actually a large health problem. So that's part of that environmental sort of, or problems that will be solved as well."*

The reduction in noise levels was tied not only to personal vehicles, but also commonly to electric buses and other heavier duty vehicles. Heavy duty forms of transportation, namely city buses and lorries, posed a challenge for city planners with road noise impacting time nearby houses. As R73 describes, the future of urban planning could be quite different given the removal of noise from transportation:

> "*I think there a lot of things like pollution, being quiet. You can also drive inside the buildings. There are a lot of new possibilities with the EV's*."

The possibility of driving vehicles inside buildings may sound a bit farfetched, but many experts recognized the substantial benefits electrification would have on the optimization of traffic planning, and its subsequent impacts on housing prices, city planning, and individual's health. For example, R248 discussed how bus drivers were healthier after switching to an electric bus:

> *"After 10 hours of driving an electric bus, they are about as tired as if they have been driving a diesel bus for 7 hours. So they came home after the day, and they were able to do many things which they had not, were able to sleep more than before, do training or proactive [exercising]"*

Next, the third most discussed benefit was the better performance of EVs as compared to internal combustion engine vehicles (ICEVs). These discussions often included the relative better acceleration and energy efficiency of EVs due to their instant torque, the more comfortable driving (e.g. less vibration and noise), and overall better handling and weight distribution. Indeed, many experts actually viewed the better performance of EVs as a central impetus to implement EVs. For example, when discussing reasons for government to develop EV policy, R196 told us:

> *"[W]hy would you do electric car? Well, because it's a superior technology then. If for no other reason, do it for that."*

It may seem counter-intuitive for the government to incentivize a technology if only to increase the welfare of private drivers, but, for R196, the better performance of EVs warranted government support. But pushing aside the question of the role of government, the benefits of EVs go far beyond simply costs and carbon.

Moving along to the fourth most common benefit, the economic savings of EVs was not as widely discussed as the authors expected, given its prevalence in the literature (Wu et al. 2015; Carlsson & Johansson-Stenman 2003), as only a quarter of experts discussed economic savings in any manner. Looking deeper into those who did discuss it, an overwhelming amount of experts explicitly characterized the economic benefits from an individual point of view, as opposed to the potential societal economic savings (36 to only 14, respectively). Those who did recognize the societal level of savings foresaw substantial changes to overall living cost, as R119 noted:

> *"So looking at the whole cost of transportation and mobility of the population in Denmark and Aarhus, it's going to be much cheaper in an electrical car, so it's going to lower the living cost and the production cost of the whole society to go to electrical cars."*

However, more often than not, the experts tended to focus on individual economics. While the authors recognize that individual savings is an important argument for the deployment of EVs, the lack of widespread discussion of societal savings – which some scholars calculate at billions (Noel et al. 2017) – may imply that experts could be generally incognizant of one of the largest benefits EVs can offer society. As these savings could then provide economic activity for consumers now freed from spending money on petrol.

Fifth, many experts discussed the benefit of electric vehicles in the connection to renewable electricity. Generally, the experts discussed the integration of EVs and renewable electricity in terms of renewable electricity that already existed, e.g. higher utilization rates of wind currently in the system. However, a small subset of experts (9 out of the total of 55 interviews discussed renewable energy) discussed the possibility of using EVs as a means to integrate *new* renewable electricity. Combining this with the set of experts that, unprompted, saw V2G as a central benefit EVs could provide in the future, more than a third saw the central benefits of EVs to include grid services and renewable energy integration.

Importantly, there was a wide variety of benefits beyond these five central benefits. Beyond these central topics, the remaining benefits were diverse, including energy efficiency and independency. Interestingly, despite the relatively slow uptake of EVs outside of Norway, several experts espoused the benefit that EVs are easy to integrate – either into the electricity system (17 interviews), or into the daily travel patterns of society (6). Perhaps mirroring developments in the solar industry (The Solar Foundation 2017), in 12% of the interviews experts expected EVs to bring new job opportunities and increase local economic activity. Notably, an interesting benefit of EVs discussed in 4% of the interviews was the convenience of charging at more convenient locations, namely at one's home or one's work, thereby reducing the necessity to go the gas station. In fact, experts such as R245 believed that this was a benefit that needed to be better communicated to the public:

> *"And then I think people that get really used to the electric vehicle, they like the convenience, because typically they only charge the vehicle at home or at their place of work. That is also very convenient. And I think that is something that is under communicated to potential EV buyers. Because that is really convenient, if you don't ever have to stop by a refuelling station and make a detour for that."*

Of the remaining benefits (of which fewer than 2% of the experts brought up), the responses were increasingly creative. For example, these benefits included the idea that EVs would lead to both safer cars as well as less congestion with the advent of automation technology, where automated and autonomous vehicles will be inherently powered by electricity. Additionally, some presented the idea that EVs would lead people to change their behaviour in other ways to become more environmental. For example, while we were discussing their own behaviour changing after driving an EV, R85 articulates:

> *"[I]t does change people, a lot of people say that. So there is a lot of, that's a very interesting psychological thing that is going on, just because you have a different car."*

Thus, implementation of EVs may increase individual's knowledge of energy use and environmental impacts of transport demand. Others also believed that EVs would change people's behaviour to increase their willingness to consider new modes of transportation, such as car sharing and automated vehicles.

Overall these results, see Figure 1, show that there is to some extent a heterogeneous narrative in the main perceived advantages of EV technology. While the positive environmental attributes of carbon and local emissions dominated discussions, EVs embody other benefits that are not to-date well documented in the literature or other outlets. The advantages of noise reduction, the social economic benefits, convenience of charging, or better performance are beginning to be apparent to experts on the field.

3.2.3.2. V2G Benefits

The benefits of V2G are much more pluralistic compared to the experts' view of EV benefits. Overall knowledge of V2G was less defined; only 149 interviews, representing just under 66% of the sample, brought up some benefits of V2G, with many being unfamiliar with the topic (compared to over 95% of the interviews expressing a benefit of EVs). We categorized those who did discuss a benefit of V2G into 25 categories, summarized in Figure 13.

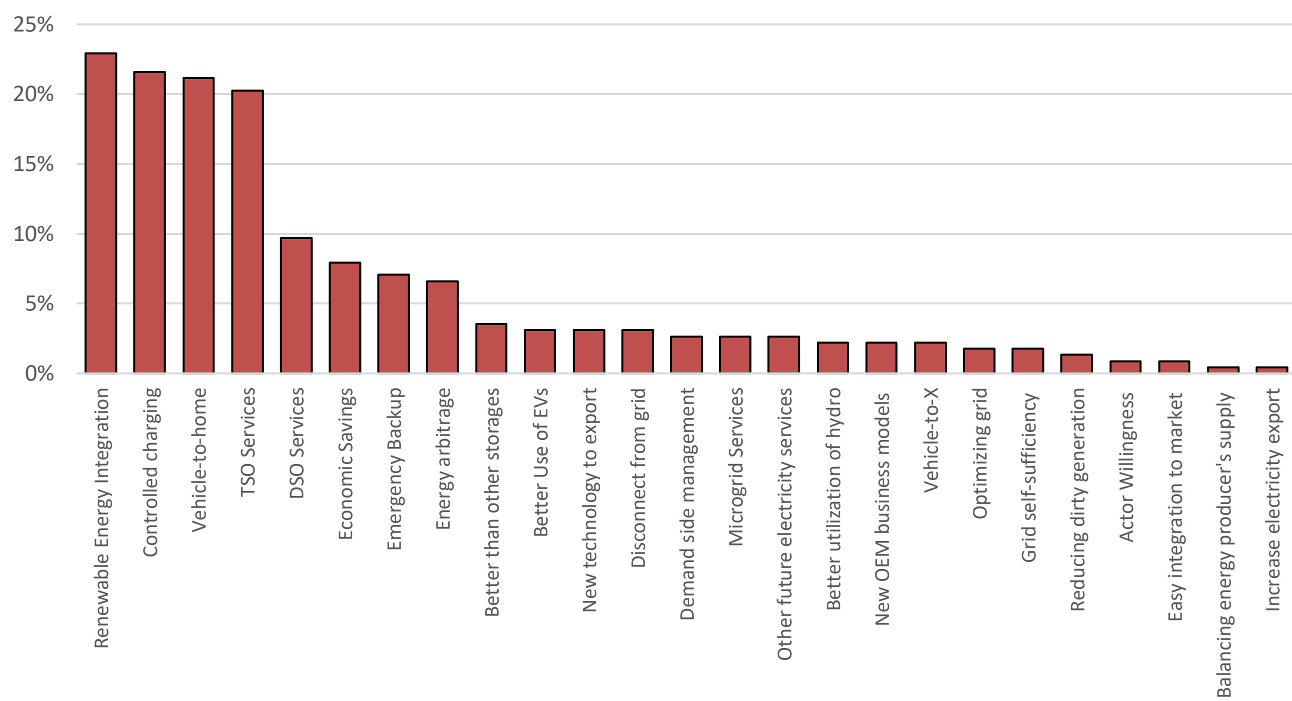

Figure 13. Co-Benefits of Vehicle-to-Grid Identified by Interviews. Note: Constructed by authors.

First and foremost, the most discussed benefit of V2G was its capacity to integrate new intermittent sources of renewable energy, brought up by 52 experts. Surprisingly, V2G was twice as likely to be discussed explicitly in terms of solar energy (33 experts) compared to wind energy (only 15). For most experts, the benefits of V2G were less focused on utility scale wind (despite the Nordic region's wind resources), but rather, the benefits focused on more local solar production. Indeed, though the connection of V2G and utility-scale renewable energy integration is well established in the literature (Lund & Kempton 2008; Noel et al. 2017), the experts connected the idea of renewable integration more closely to vehicle-to-home (V2H), another widely discussed benefit of V2G. For example, R61 overtly preferred connecting solar and V2H:

"*If you think you're getting solar and wind but especially solar to store, you could connect EV to a house and even out the highs and lows in your house. That's something that would make more sense in a way.*"

For many experts, solar PV and V2H was a natural connection and perhaps more intuitive than the complex services V2G could provide, such as frequency regulation. Surprisingly, V2H was slightly more common than the variety grid services that V2G could provide (see below). The gravitation of experts towards V2H is quite peculiar given that a recent systematic review of the V2G literature indicated that the literature focused substantially more on grid-level services rather than V2H (Benjamin K. Sovacool, Noel, Axsen, et al. 2018).This perhaps reflects a disconnect between academia and industry, where V2G remains quite a novel concept and only until recently more publicly available pilot projects are being developed outside of the US and Denmark.

The next most discussed benefit of V2G was simply controlled charging, also known as smart charging or V1G. The context of controlled charging varied widely among the experts, with some seeing it as a stepping stone and for others, the upper bound. First, controlled charging seemed to be a very intuitive benefit of V2G for many of the experts who were unsure of the future viability of V2G. For example, R53 saw controlled charging as the first and most certain benefit of V2G:

> *"[T]he first step is probably just, not storage, but it's basically that you can decide when, that utilities should be able to decide when you are recharge your vehicle."*

However, others were more uncertain about the prospects of V2G beyond controlled charging, as R137 expressed their concern of the additional complexity of V2G compared to controlled charging:

> *Smart charging the first place, because that must be created and that's the easy one that the cars are charged…but of course vehicle to grid is much more complicated.*

On the other hand, other experts were more certain of the future of V2G, but still clarified that controlled charging would be the first step of a clear path that would explicitly expand to bidirectionality. R121 saw controlled charging as the stepping stone to V2G:

> *"Yea, first layer for the benefits comes from small-scale demand response services, mainly to reduce the charging power, in a cluster of chargers, locally or in a wider clusters. And, the second phase of that is of course vehicle-to-grid, so moving the electricity both ways."*

Nonetheless, controlled charging was conversely characterized as the ceiling of V2G, as many experts saw it as the only valuable service EVs would provide, and were sceptical that bidirectionality would add any value. As R114 showed, only flexibility on charging the EV was valuable:

> *"I could easily see some flexible measure to the battery. I cannot see the opposite way round that the battery delivers electricity to the grid, that would not be easy for me to understand."*

Likewise, R110, who was wary that bidirectionality could provide any significant levels of value, reiterated that controlled charging was an obvious benefit:

"And of course, I can see smart charging electric vehicles of course is a major obvious thing to do."

Controlled charging was portrayed in a variety of contexts, often conflicting. However, as indicated above, the majority of these experts did not connect it to the wider set of services and benefits V2G could provide (Knezovic et al. 2015; Kempton & Tomić 2005b), for example, finding that V2G could provide net revenues of around $2,500 per year for participation in ancillary service market participation. Over the lifetime of a typical vehicle, these revenues add up to around $20,000 to $45,000 in the U.S., depending on the electricity grid (Noori et al. 2016). While this may be indicative of V2G's relative immaturity, it may also show the lack of cognizance, even among transport and electricity experts, of the wider variety of benefits that V2G could provide (as compared to the many creative benefits experts discussed for EVs), and is actually currently providing within the Nordics, in Denmark (Pentland 2015).

The two next most common topics were more specific discussions of the benefits V2G could provide to the grid, including both the Transmission System Operator (TSO) and the Distribution System Operator (DSO), with 31% and 15% of experts discussing each respectively. For TSO services, the most common subtopic was providing ancillary services, mostly frequency regulation, though one expert discussed spinning reserves. The other two subtopics were dealing with intermittency on the grid and peak shaving, often discussed in tandem. However, some experts believed that the benefits of V2G peak shaving were overstated, and the focus should be on ancillary services. For example, R140 dismissed peak shaving as insignificant as compared to ancillary services:

> *"Peak shaving, these are just nonsense, you don't get enough money to cover the aging of the battery. The axillary services and the frequency regulation is the one that you can actually get, you can actually make money."*

Moving further down the wire, common topics of DSO services were the capacity for V2G-capable cars to delay investments in upgrading local transformers and addressing local congestion. Some viewed DSO services as a complement to V2G providing TSO services, but others viewed DSO services more dependent on the grid quality at which the EVs were located. For example, R133 believed that the V2G belonged more in rural areas, and explicitly not urban, where the grids were weak and needed help:

> *"[M]aybe coming from using the EVs as storage then and if the network company or some other operator would be allowed to somehow manage the batteries, there, then that would be or could be maintaining the grid, especially in the rural area, I think it has less importance in the city areas, but especially in the rural areas."*

Although experts believed DSO services would be of immediate value, some were sceptical that the market was structured correctly in order to handle V2G flexibility. For example, R84 was uncertain about the future of V2G in the DSO context:

> *I think that's a toughest question to answer because this necessitates this kind of market or, I'm kind of, I'm not really sure I believe that there will be the DSO market, but at least some mechanisms where the DSO can start or invoke this response and also including V2G and there also be insufficient services to do so, I think there will have to be pragmatic very easy solution for that.*

Moving onto the next topic, the economic benefits of V2G were discussed substantially less frequently than for EVs. Whereas 58 experts discussed the economic benefits of EVs, only 18 experts discussed the economic savings as a central benefit of V2G, comprising only 8% of the experts. Of those 18, the vast majority discussed the economic savings in terms of individual consumers (14 experts), whereas only 3 discussed the potential savings of V2G to the grid, similarly mirroring the narrative frame for economic savings of EVs. The subset of experts that were cognizant of actual estimates of individual revenues from V2G framed these benefits as substantial and with obvious benefits. For example, as R130 puts it, earning around €1,400/year makes V2G "obvious":

> *"[W]e are still what we said at the beginning that we expect the revenue per car to be about ten thousand Danish kroners per car, it seems we are very much on our way to those kinds of figures. So, you know, it's an obvious business case there."*

In addition, R98 imagined that the revenue potential of V2G would incentivize individuals to participate:

> *"The potential is gigantic…If you see your neighbour is earning 100 euros a month by being part of a scheme, you would feel stupid if you don't do it yourself."*

For some experts, the economic benefits of V2G was an indisputable benefit, particularly for individuals. Practically all the estimates of V2G revenues across experts were equal, circling around 900 Danish kroner or €120 per month, seemingly based on the revenue potential from the pilot project in Denmark. Nonetheless, the vast majority of experts did not discuss precise (or any) revenues, and may have not been cognizant of the full extent of the revenue potential of V2G.

Beyond economic savings, some experts viewed V2G as providing non-economic services as well, namely emergency backup power. Many of the experts who mentioned the idea of emergency backup likewise discussed this in context of Nissan's efforts in Japan, as R233 notes:

> *"I see why they are doing it in Japan, in countries where they are struggling the earthquake, you need the grid or the power. And I know that they are talking about the future, and that they would be a way of have vehicle-to-grid solution."*

In many cases, the experts noted emergency backup as a theoretical benefit that was better suited for countries like Japan, which faced more natural disaster threats. However, other experts still viewed emergency backup as providing value within the Nordics. R163 notes that V2G can provide essential and potentially lifesaving services in Finland if the electricity system experiences a blackout due to winter conditions:

> *"If you gives you additional value or market but, I think that's something which is really needed for in some parts of Finland … So it means that you have an elderly house, you may have zero backup, you may have your water purification system for the community, you have zero backup if the company who is taking care of that, has not been thoughtful."*

Likewise, R179 also added:

> *"Another alternative is that of course when you have your own house or apartment you use that car electricity to supply that household or the limited regions because then you can in a way use that car for the critical loads which you really need that lights, and maybe the fridge and that kind of things. Which doesn't require that much electricity."*

While emergency backup power may play an important role in safety, other services would provide substantially more monetary value to the EV owners (Sovacool et al. 2017; Kempton & Tomić 2005b). Thus it is noteworthy that emergency backup was discussed to such an extent by the experts, and could imply that either experts were undervaluing other services or that emergency backup power should not be underestimated.

Beyond the above benefits, the remaining benefits were much less frequently discussed – more than two thirds of the categorized benefits were brought up in less than 4% of the interviews. These benefits reflect the uncertainty of the future V2G could provide. For example, 3% believed

V2G could provide a number of undefined services in the future, given the capacity V2G could have available in the future, as well as changing electricity markets. For other benefits, such as micro grids, discussed by 6 experts, the potential of V2G depended on the uncertainty of a changing electricity grid– one which may become more decentralized and more reliant on storage.

Similarly, though it was not widely discussed, some experts discussed creative benefits of V2G in the context of future uses of vehicle-to-X (V2X). For example, R86 suggested that V2G should be used for a much wider variety of applications, focusing more on personal uses:

> *"Nissan is the only one who says you can use the battery and the warranty is there without compromise, so I think easily, their next step could be doing this and I think a lot of people would have fun about that, you can make a party at the beach, with light and everything, with this car, it can be a very powerful feature that you can use for anything, also vehicle-telescope, or whatever, just imagine what you can use it for."*

While much of the V2G topics were less innovative compared to the benefits of EVs, R86 surely brought some novelty to the benefits by discussing vehicle-to-telescope. Other experts added that V2G could be utilized for other unique uses, such as music festivals, electric barbecues, road construction workers, gardeners, and charging phones, as well as more traditional V2X uses, such as vehicle-to-building (V2B) or vehicle-to-vehicle (V2V). The powerful versatility of V2X is a unique individual benefit, but focuses less on the economic benefits that V2G could provide TSO or DSO grids that the literature tends to focus on. So while V2G is primarily driven by grid considerations, insights like these show alternative business cases and benefits for other sectors.

The experts provided a wide variety of benefits that go beyond the usual economic and renewable integration benefits discussed in the literature. On the other hand, many of the complex V2G benefits, like various TSO and DSO services, may need to be better communicated even among experts, and will likely pose challenges to non-experts. For example, we found that outside of a select few electricity grid experts, the other experts were generally incognizant of the attractive economic benefits of V2G participating ancillary. Considering that this is arguably the highest magnitude benefit, particularly for consumers (Sovacool et al. n.d.), it is important for these types of experts, particularly transport policymakers and researchers, to better understand the full benefits of V2G beyond renewable integration. Thus communication of the benefits V2G could provide not only needs to be improved, but also expanded to other various benefits described in Figure 2. We propose that future research should be undertaken to explore how this communication can be implemented, whether it be through increased academic focus within the transport field on V2G, bridging this apparent gap between transport and electricity, or alternatively, more outreach from electricity grid experts to the transport sector.

3.2.4. Conclusion and Implications

In both the cases of EVs and V2G, the benefits expressed by the experts went extensively beyond the central benefits presented in the literature. While our sample of experts acknowledged the central EV benefits around economics and emissions, they also discussed a wide variety of creative benefits. V2G benefits also captured the common themes of the literature like renewable energy integration and various grid services, but also submitted interesting benefits of lesser economic focus. We therefore propose that future research in personal mobility policy and development should weigh the full assortment of benefits of EVs and V2G and be open to novel and creative use of both technologies.

For example, looking forward, noise reduction may provide an important benefit not only on an individual level for the vehicle driver or passengers, but also for non-users such as cyclist and pedestrian and ultimately for urban planning and transportation; which certainly merits consideration when weighing the benefits and costs of electrifying mobility. On the other hand, benefits like noise reduction and better performance of EVs as well as V2X and emergency backup may seem like private individual benefits. However, firstly, the individual focus does not warrant exclusion of these benefits in transport policy analysis (as the literature also often investigates private economic savings) and still may improve societal welfare. Secondly these benefits also impact those who drive as parts of fleet, such as electric buses, and reduction of noise and better handling may improve the safety and performance of public transportation, as drivers will have less headaches from the noise and better responsiveness during acceleration and stopping. Moreover, these benefits also impact non-users, like bicyclists and pedestrians or nearby habitants, reducing noise and increasing safety. Therefore, these secondary advantages of the electrification of mobility, while difficult to quantify, should not be overlooked when researching and creating transport and other related policy.

There was more plurality on the benefits associated with V2G, which is to some extent related to the newness of the technology and concept. This was seen in the association of V2G primarily with residential solar PV and vehicle-to-home advantages, rather than the literature-focused grid services. As pilot projects are more frequently implemented, the knowledge of V2G around its grid services potential and economic gains should and probably will be better considered amongst experts and users. But at the same time, the literature should not continue to ignore valuable non-economic benefits of V2G like emergency power backup and V2X. Moving forward, promoting the benefits of V2G and EVs may also address the social barriers they face (Sovacool & Hirsh 2009). For example, increasing the versatility that V2G can offer individual consumers may decrease resistance to using their EV for other services that may improve grid reliability and offer other wider-scale social benefits.

Clearly, the full assortment of benefits should be considered when considering EVs and V2G in transportation and economic policy analyses. Including various other benefits, like noise reduction and V2X, these may alter the analyses above such that it "tips" the scales and changes the results, especially when considering the myriad of costs and barriers that these technologies face. At the same time, the authors admit many of these benefits may not warrant inclusion, or may be difficult to include in future analyses. Thus, we also call for future research to validate the magnitude of the benefits suggested by the experts for both EVs and V2G, as well as monetize as many as possible to allow for easy integration into cost-benefit analyses.

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4. Theme 3: the system level

The second research question is answered by introducing the following articles:

1. Zarazua de Rubens, G., L. Noel, J. Kester, B. Sovacool. (2018). '*The market case for electric mobility: Investigating electric vehicle business models for mass adoption*'. In review with Energy Policy.

2. Noel, L, Zarazua de Rubens, G & Sovacool, B. (2018). '*Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark*' *Energy*, vol. 153, pp. 628-637. https://doi.org/10.1016/j.energy.2018.04.076

The papers presented on this theme look into the analysis of the system level of electric mobility. In particular the first paper deals with the analysis from a business perspective, whereas the second one focuses on the system impact of EVs and V2G exploring the potential social benefit of these technologies.

4.1 The market case for electric mobility: Investigating electric vehicle business models for mass adoption

The fifth article presented in this dissertation (first of this theme) considers that many structural challenges remain to be addressed around the electric vehicle socio-technical system as the technology progresses from niche to early and late mass markets. This study investigates the challenges for electric vehicles focusing on their current and future business implications. For this purpose, we rely on a robust sample of 227 semi-structured interviews, conducted by the authors, with transportation and electricity experts from 201 institutions across seventeen cities in Denmark, Finland, Iceland, Norway, and Sweden. Our findings show that EVs currently face an unfavourable business case, led by the legacy of the petrol and diesel car industries, and national market conditions. This results in an unsuitable business model and supply chain that compromises EV production and market offerings. Additionally, we find that for wide diffusion in society, EVs will change the traditional automotive selling chain, directly affecting selling methods (i.e. dealerships), maintenance revenue streams and refuelling (recharging) structures. It is therefore essential to adopt new models, practices and methods of business that are suitable for EV diffusion.

4.1.1 Introduction

Electric vehicles (EVs) are recognised as the most feasible technology option to decarbonise passenger transportation across the world, particularly when combined with low carbon power systems (Kennedy et al. 2014; Needell et al. 2016; Richardson 2013; Muneer et al. 2015). However, EVs have traditionally faced barriers for their mass deployment (Nilsson & Nykvist

2016; Berkeley et al. 2017; Tran et al. 2012) and, despite having positive trends in new car sales, in 2017 EVs only accounted for around 0.2-0.3% of the total global passenger fleet (International Energy Agency 2017; International Energy Agency 2018).

Considering EVs are another form of automobility but with electric drivetrain, this technology competes directly with the well-established internal combustion engine vehicles (ICEVs) market. This established automotive regime, led by automotive Original Equipment Manufacturers (OEMs), has contributed to the development of social norms around conventional cars and their use, which represent a strong barrier for electric vehicles (Nykvist & Nilsson 2015; Urry 2003). Recent research has noted that EVs have an unfavourable business case in comparison to petrol and diesel vehicles which is a result of both the routines and expectations about mobility that stem from the use of ICEVs and government policy that has favoured fossil fuel-based vehicles (Zarazua de Rubens et al. 2018; Nieuwenhuis 2018); which is evidenced at a retail level at automotive dealerships where salespeople tend to sell ICEVs instead of EVs (Zarazua de Rubens et al. 2018).

A critical point for EVs is that they are invariably compared against conventional cars in terms of driving capability, style, use and sentiment. For this reason, a plethora of studies have explored the challenges electric vehicles face for social-wide adoption, focusing on different elements or stages across the life cycle of the vehicle and its supply chain, as well as the optimal configuration for the EV ecosystem; particularly its recharging network (Brooker & Qin 2015). Such studies include system analyses on EV adoption and their potential effect on power grids (Noel, Zarazua de Rubens & Sovacool 2018; Noel et al. 2017; Gnann et al. 2018), to technical elements, such as battery capacity and driving range (Kempton 2016; Bonges & Lusk 2016; Dimitropoulos et al. 2013; Pearre et al. 2011a).

and also socioeconomic elements like taxation and policy incentives (Mersky et al. 2016; Bakker & Jacob Trip 2013; Harrison & Thiel 2017). Consumer-focused studies have investigated the drivers of acceptance such as pro-environmental attributes (Vassileva & Campillo 2017; Egbue & Long 2012; Rezvani et al. 2015) and other user related challenges linked to charging infrastructure(Sun et al. 2017), particularly, range anxiety (BROAD 2016; Noel, Zarazua de Rubens, Sovacool, et al. 2018). Recently, research has further began to focus on consumer segments for EV adoption exploring the potential mainstream EV markets.

Notably, EVs are not only a vehicle technology for mobility but, based on their power source and power train, can be involved more naturally in the digital world (i.e. via mobile phone apps), and even be integrated to other systems such as the power grid, via vehicle-to-grid (V2G) (Kempton & Tomić 2005a). Despite these inherent differences, the automotive industry (traditional OEMS) continues to manufacture EVs in the same manner as ICEVs and more, presents them to consumers under the same lens as a conventional car (Nieuwenhuis 2018). This approach is on one hand due to the lack of knowledge in how to develop and push EVs downstream, but also comes from an unwillingness to do so, due to the large investments placed on ICEV infrastructure (Nieuwenhuis 2018).

EVs thus likely require new business models and structures that are purpose-made for the technology, where EVs are not compromised but rather optimised (Nieuwenhuis 2018). Successful examples already exist, such as Tesla, but also plenty of failures, the most well-known of which perhaps the battery-swapping model of Better Place (Noel & Sovacool 2016). Importantly, these new models have typically come from new companies not involved with the traditional car regime. Furthermore, even if successful, the potential of these new business models for social-wide EV adoption has remained rather limited. In this way, there is limited research on EV business models and business cases to draw from, with a few notable exceptions (Beeton & Meyer 2014; Nieuwenhuis 2018; Kley et al. 2011). While these few studies have propositioned alternative tools for analysing EV business models models (Kley et al. 2011), or explored current industry developments and propose new alternatives, they have lacked a robust and compressive insight into the minds of experts leading and operating the automotive industry (Nieuwenhuis 2018; Bohnsacka et al. 2017). This in particular to understand the reasoning behind the automotive industry, the barriers it faces to integrate a new vehicle technology into its core business, and the interaction between the established ICEV market and the emergent EV market. Moreover, due to the new (the last 10-15 years) and technology-driven nature of EVs, the technology and market of electric vehicles is bound to change rapidly. For these reasons, continuous research with up-to-date primary data is essential in fomenting the development of EVs and their potential business models.

In this paper we set to explore the business challenges of electric vehicles with the aim to provide suggestions that support social-wide adoption. For this exploration, we rely on an original dataset of 227 expert interviews with individuals employed in sectors related to electric mobility across the five Nordic countries. In doing so, we present their perceptions on EVs and what challenges these vehicles and their development raise for industry and society, as well as the perceived opportunities for adoption. Additionally, we discuss the potential for EVs adoption based on business structures and selling strategies. The contribution of the analysis is further supported by the inclusion of data from five different national markets, each with their own tax, regulatory, commercial and social conditions as well as different stages of EV penetration. These markets include the global EV leader Norway, to recent intermediate adopters in Sweden and Iceland, and other less developed EV markets of Denmark, Finland. Below the study presents the methodology with a description of the data and assumptions used to create the analysis of the study. It then presents and analyses the results based on the business challenges for potential EV adoption.

4.1.2. Research methods and empirical strategy

To explore the business context of electric mobility the authors relied primarily on an original dataset of 227 semi-structured expert interviews with 257 participants from over 200 institutions in the five Nordic countries. A brief summary of the interview participants is presented in Table 18. This methodology was applied on a regional context taking the five Nordic countries as place of study, considering these countries are traditionally recognised for having relative progressive climate, energy and transport policy agendas, and emerging as leading nations in electric vehicle uptake (Norway), or pioneers of wind energy (Denmark), or geothermal energy (Iceland).

The interviewed experts represent a diverse array of stakeholders involved in transportation, energy and the environment. These interviews generally lasted between thirty and ninety minutes, where participants were asked several questions about the business context of electric vehicles and vehicle-to-grid. With previous consent, each but one expert encounter was recorded and given a unique respondent number. Once data collection was concluded, each interview was fully transcribed and subsequently coded on an argument level in NVIVO with each new argument getting a new code. Here, the coded themes for each discussed topic were not predetermined but based on the data available.

Classifications	**Interviews (n=227)**	**Respondents (n=257)**	**% of Respondents**
Country = Iceland (Sept-Oct 2016)	29	36	14.0%
Country = Sweden (Nov-Dec 2016)	42	44	17.1%
Country = Denmark (Jan-Mar 2017)	45	53	20.6%
Country = Finland (Mar 2017)	50	57	22.2%
Country = Norway (Apr-May 2017)	61	67	26.1%
Gender = Male	160	207	80,5%
Gender = Female	40	50	19.5%
Gender = Group	27		
Focus = Transport or Logistics	73	81	31.5%
Focus = Energy or Electricity System	63	75	29.2%
Focus = Funding or Investment	10	12	4.7%
Focus = Environment or Climate Change	12	16	6.2%
Focus = Fuel Consumption and Technology	22	23	8.9%
Focus = Other	13	14	5.4%
Focus = EVs and Charging Technology	34	36	14.0%
Sector = Commercial	68	70	27.2%
Sector = Public	37	46	17.9%
Sector = Semi-Public	40	51	19.8%
Sector = Research	37	39	15.2%
Sector = Non-Profit and Media	12	13	5.1%
Sector = Lobby	23	25	9.7%
Sector = Consultancy	10	10	3.9%

Table 18. Overview of Expert Interviews. Source: Authors. Focus represents the primary focus area of the organization or person in question, Sector represents the sector the company was operating in (i.e. semi-public referring to commercial companies owned by public authorities, like DSOs).

4.1.3. Results: A business case against electric mobility?

Overall, our interviews indicate that EVs currently face an unfavourable business case that results, for the most part, in unprofitable product lines for industry and unaffordable vehicles for consumers. For industry, the development of EVs particularly affects the nested investments on their ICEV product lines, selling methods (i.e. dealerships), component manufacturers, maintenance networks and refuelling (recharging) networks. These, in turn, create deterrents for OEMs to dedicate themselves to the development of EVs and have resulted in inefficient production and selling strategies, which are based on routine like ICEVs business practices rather than tailored to the characteristics of EVs and engaging with consumer uncertainty. Additionally, there are business challenges that arise with the potential large-scale penetration of EVs, even once business structures are fitted to optimise EV development. In this way interviewed experts highlighted questions of scalability and sustainability of production lines, such as manufacturing capacity of batteries or development of charging infrastructure models. Below we present our results in four themes: unfavourable business case, maintenance business units, supply and manufacturing capacity and charging infrastructure.

4.1.3.1 Fossil fuel favouritism

One of the main, if not the biggest, barrier for electric vehicle adoption that emerged in our interviews is the higher retail price in comparison to petrol or diesel vehicle options, which results in consumer disinterest due to unaffordability and therefore lack of product sales. Additionally, on the supply side, EVs are categorised as not profitable due to high production costs and lack of after-sales revenue streams which deters industry players willingness to engage and sell the technology. The high cost and high price of EVs creates significant difficulties for business models and thus social-wide adoption, as R034 states:

> *"if somebody will say to me now: "you need to only sell electric cars", I would close down the business."*

The lack of overall profitability has resulted in OEMs having to force EVs downstream onto dealerships, to attempt to promote existing EV offerings, even when dealerships are openly reluctant to engage with the technology. This is underscored by the fact that EVs do not provide dealers with further revenue sources that ICEVs would, resulting in active disincentives to sell an EV, as R107 explains:

> *"From a profit point of view our dealers as worse off as we are. They are losing money on every EV they are selling. They generally hate the product because there is no business in it for them. It is something we are forcing on them. If we weren't forcing it on them, they wouldn't have the demo vehicle."*

Considering that EVs are the economically inferior option from the perspective of the dealers and the industry in general, it is unsurprising that OEMs have trouble justifying the sale of EVs in favour of ICEVs to their shareholders. In this way, R077 argues that industry, dealerships and salespersons have reacted to EVs in a rational way to the to-date automotive market conditions:

> *"[Industry and dealerships] have reacted in an economic rational way maybe, because this is a huge investment and they are not sure whether they'll get their money back from the investment"*

On the other hand, not all the experts believed that the onus lied on the OEMs. Some experts, such as R101, attributed the current slow EV adoption not to the lack of investments on the supply side, but rather argued that EVs are not available for sale at dealerships simply because consumers do not want them:

> *"I'm absolutely confident that car importers or retailers have the product on the shelf for which there are customers. If there are customers for electric cars, they [would] have electric cars all over. It might take some months before they are there, because there is a limited production capacity perhaps, but if the customer is asking for it, it's there."*

This can be misleading considering that for the most part, the average consumer may not even be aware that EVs can be a real purchasing option. Instead, it is frequently automotive OEMs, car dealerships, and salespersons that direct consumers further away from EVs; as recent research has shown (Zarazua de Rubens et al. 2018).

Notably, the automotive market is an intertwined space between industry and government where both have created unfavorable conditions for electric vehicles. Policy directly affects retail markets and eventual EV adoption, which is most evidenced perhaps in Denmark and Norway, but in opposite ways. Norway is the recognised global leader on successful monetary and non-monetary policies for EV adoption whilst, as research has shown, Danish policy makers have created an impossible market space for EVs to operate(Zarazua de Rubens et al. 2018). This is noted by R107:

> *"We are only a company. I have proposed internally that we stop selling EVs in Denmark. We need to make money. If we are not pushed by politicians so that it makes sense for us to sell EVs, we are quite fine with selling vehicles that run on petrol and diesel, it's just bad for society."*

The reflection of R107 also points to the complacency of traditional OEM industry players, where despite stated aspirations for sustainability and providing cleaner forms of mobility, the bottom line is directed purely by business interests. Such a view was corroborated by R126:

> *"I would say the interest is very limited [on EVs] simply because the bottom line [is], money talks"*

There is a negative cycle for EVs everywhere, but in particular in markets like the Danish where policy strongly favours ICEVs(Zarazua de Rubens et al. 2018) and also OEMs are reluctant to adapt business practices for EVs and dedicate investments on the technology. As R107 further elaborated:

> *"We are under scrutiny every time we propose investment in EVs [to our shareholders]."*

Internationally, OEMs are seen reluctant to dedicate investments towards EVs due to the huge infrastructure assets that lay within the ICEV sector, with returns on investments (ROIs) that remain to be captured, in addition to the ongoing, and new, yearly investments on ICEV technology. These investments are not only monetary but also about creating new models that are fit for EVs rather than recycled from traditional ICEV technology(Nieuwenhuis 2018). Many experts agree on this as R143 for example mentioned:

> *"I am almost a hundred percent sure that if the Tesla never showed up, we [wouldn't] have electric vehicles, because those big companies like BMW, Mercedes, Volkswagen, GM, this kind of, even Japanese, they are protecting their existing product lines."*

R084, furthers this point by mentioning that OEMs have no incentive to invest on EVs since they would be affecting their own markets:

> *"all the assets they have in the ICEV world, they would have to invest a lot, and why would they invest to take their own market?".*

R107 adds to the point, but also elaborates that EVs will be supported when they appear to be profitable for industry, their attachment is not to a particular technology but the business of it:

> *"Of course from a business perspective, we are unable to support an initiative that would decrease the car market because that would decrease our potential income. But if the combustible market decreased and the EVs market increases accordingly so that the total is the same, we would be happy to support that."*

Nationally, governments (outside of Norway) do not harmonise transport policy and where currently the net market benefits still favours ICEVs making these vehicles the most attractive option for industry to sell and consumers to buy(Zarazua de Rubens et al. 2018). These negative effects for EVs are evidenced on actual vehicle purchases where, since 2015, multiple policy changes in Denmark that restarted the introduction of taxes on EVs completely stalled sales in the country(Zarazua de Rubens et al. 2018). R036 describes the international up-to-this point situation with electric cars as:

> "*If I had a dealership, I would tell my guys 'hey guys, sell gasoline cars, the margin is there and we'll get everything'. You would be stupid [to say]: 'hey guys, focus on the electric cars, we'll get nothing when we sell it or we'll get small thing when we sell it, but nothing after that, let's go for that guys'. The model is not there, so it's not like a conspiracy*."

Consequently, there continues to be a need for business models that are fit for EVs, where we create manufacturing processes, marketing and training campaigns, sales and after-sales strategies that optimise the deployment of electric vehicles and support its wide-scale adoption. Particularly in markets where governments cannot recreate, or are reluctant to do so, the monetary EV incentives of Norway that has carried the world leading EV adoption rates of the country.

4.1.3.2 Mad about maintenance

The lack of business case can be linked to different elements as we have seen on the previous section, however the after-sales markets, in particular the lack of maintenance EVs need, comes as a key barrier that deters EV adoption, according to the interviewed experts. While it is recognised that EVs do not require as much maintenance as ICEV options(US Department of Energy 2018; McMahon 2018) and this affects the overall profitability of the vehicle, both the level of impact and also the potential alternatives for OEMs remain relatively underexplored. Our respondent, R010, explains the rationale of industry behind the after-sales market of EVs and ICEVs as:

> *"there is a lack of incentive for the big companies there [with EVs], because they foresee if you sell, a regular gasoline car, 'I am Volkswagen, I know for every car that I sell, I can say I have sold a subscription to certain revenue over the lifetime of a vehicle, say 7-10-15 years, and I know my dealership support network, there an instant subscription of certain revenue. Because the car will have to come in, I will sell some spare parts, I will blow up prices so I will continue to get revenue from that vehicle. If it is an electric vehicle, I don't hear from the client again."*

In our interviews, experts mention that EVs have 80%-90% less maintenance expenses post-sale in comparison to ICEV, as for example R010 continues to elaborate:

> *"The maintenance is maybe 10% of it. [OEMS] either have to gain the same revenue by either having to price the EV a lot higher or come up with other ways to gain money from it."*

Even more striking, R158 mentions that for car dealers the service and maintenance unit is about 50% of their entire business, and therefore the transition to an all-EV sales portfolio means that almost half of the business revenue would cease to exist:

> *"a little bit less than half of the company money is from selling cars and about half of the money form service business. So this is also something that they suddenly consider that of course EVs don't need much service and they are decreasing their business."*

R114 mentions that the lack of post-sale maintenance remarks a superior technological position for EVs and it is of certain benefit for consumers, however it creates concerns for the automotive industry and a critical need to develop new revenue streams if EVs are set to become the mainstream mobility option:

> *"they say at least save 80% on maintenance on electric vehicles. Because there's nothing wrong with them. There's no oil change there's no, oil filter, there's no tail pipe. So that's a huge challenge in the industry to come. How are we going to make money when we have mainly EVs?"*

To which R036 mentions there is no other solution than changing the existing business model:

> *"they will have to change the business model. They can't afford these big showrooms, they can't afford all these big, bunch of people, because the car is just, you sell it its gone...[If not] they will slowly die, like Kodak, because there will be others."*

In this thread, the lack of maintenance does have a direct impact on the core business of OEMs and car dealerships but this is more of a longer-term perspective, when full-EVs become mainstream. In the interim, as R233 mentions, the automotive industry has Plug-in Hybrids (PHEVs) which have a small electric battery but, for the most part, their core is still a combustion engine that runs on petrol or diesel. PHEVs are thus being pushed into the market by OEMS as it allows them to comply with European and US fleet emission targets and consumers desire for more range, but also to continue to feed the current petrol and diesel infrastructure and maintenance networks. As these can continue to serve PHEVs and provide significant revenue for automakers and its surrounding network, which an explanation into why the automotive industry opting to push PHEVs instead of full electric. Interestingly, however, R233 mentions EVs have impacted certain car lines, which have been taken off-line due to the reduced demand, particularly of diesel engines.

Ultimately, the lack of after-sales market is a pressing barrier for EV adoption considering OEMs have so far continued to operate under traditional automotive supply structures, which are dependent on maintenance revenues for each sold product. However, this has and will continue to force the automotive industry to innovate and go beyond the business of simply selling cars. As R114 notes:

> *"We know this is going to happen. You can see for instance Volkswagen, they are moving into the industry of infrastructure. They are developing a huge business within the business as infrastructure provider. Because there's only much you can live off from selling cars… The core business is no longer enough."*

As a result, the future of OEM business models may change significantly as they shift from ICEVs to EVs. Currently, without a shift in their business models, the lack of maintenance revenue provides a stark disincentive to sell EVs. This can further result in the promotion of PHEVs as opposed to full electric vehicles, as shown above, since this allows the industry the continued use of petrol and diesel infrastructure and support networks. Therefore, if decarbonisation targets are meant to be fulfilled, one means of accelerating the adoption of full-EVs may be assisting OEMs find new business models to make after-sale revenue of EVs more appealing.

4.1.3.3 Supply chain segmentation

Another key barrier expressed by experts was related to the supply chain, in terms of producing new vehicle models that fit different car segments, producing the mass volume for EVs to eventually meet mainstream demand, and also producing infrastructure around them, particularly charging infrastructure. Here the initial suggestion is that the automotive industry has long lead times to turn one prototype vehicle into a commercially available option, and therefore highlights a two-fold complexity for EVs: the long lead time to the develop assembly lines for full-EVs and the reluctance from OEMs to do so, considering the lack of profitability of such vehicles. To this end R010 noted:

> *"…big companies said yeah we will have this [EV] available in 2 or 3 years, but in reality, they couldn't do it because of the complexity and size of the assembly line…to produce a new model…it takes [OEMs] about 5-7 years to organize and put together the supply channels, an everything, for the new type."*

Industry, R213 mentions, has had EV technology available for commercialisation but has not had the capacity to put the infrastructure in place for delivering vehicles and scale up production to meet demand.

> *"Because you have the technology but how the hell do you scale up."*

To which R010 agrees and further elaborates that is not only the OEMs themselves that lack capacity but also the component manufacturers:

> *"Sure, they have the technology, they have these and other kinds of vehicle-to-grid technology, etc. However, they weren't able to produce it because they didn't have the manufacturing capability and we're not talking about the car manufacturers but the component manufacturers."*

Every vehicle can have hundreds or thousands of different components, depending on the technology, and issues arise when each of those components needs the supply capacity to timely deliver thousands of parts for a particular product. Each of these components requires for the most part its own manufacturing plant which is intensive both in terms of time and investments. The complexity of this process is described below by R010, particularly referring to the charger that comes available with EVs:

> *"I visited that company they were trying to get funding to put up a new factory to be able to produce 10,000 units, and they needed 50 million euros or whatever it was to put up their factory and it took them 3-4 years to make a good business case, get the funding, get the foundation of their factory, build the house, go through zoning in their environment and get building permits. All that, before the chargers could start rolling out for production, and then I realized oh my god and that's just one piece of the puzzle, there are so many pieces that have to come together"*

To which, the respondent furthers:

> *"[and] if there's one component missing, then the car, a complete unit that is made of 30,000 components, will not come off the assembly line."*

This complexity of the automotive supply chain was not only referred for the purpose of producing EVs, but also to highlight that OEMs and component manufacturers have significant investments nested on petrol and diesel cars supply chains, with long term commitments and implications which limits their willingness to invest in R&D or divert production away from ICEV lines (Ishida et al. 2017). As R022 mentions:

> *"…factories have been built for millions of euros to produce petrol cars. They have a rental period of God knows what."*

A key point of focus within the EV supply capacity is the battery. There are many questions associated with EV batteries, such as their sustainability, durability and efficiency, however supply-wise experts question both the capacity to source enough materials to produce them, as well as having the actual capacity to manufacture them, as R213 mentions:

> *"The big question is how you get enough batteries. Not the price, not the efficiency. How do we replicate enough speed-up production of today's existing technology?"*

R043, a battery expert, furthers this point and elaborates on the scale of investments needed for EVs to become mainstream globally:

> *"We need 200 giga factories, but where are you going to get the materials? I don't see the government … they are not going to solve this problem. It will be private investment and investors."*

This manufacturing and supply capacity is noted by our interviewed experts as a business barrier, that governments could support also for employment reasons to create momentum for EVs and their mainstream production. However, as R043 stated above, R079 also argues that the real push will not come from the government alone, but rather its businesses that needs to get involved.

> *"Yeah it's a business barrier form the supply side exactly. And it's important that the politicians do this, to promote technology and to get the wheel spinning. But they can't do everything, they can't, it has to be a market based because we live in a market economy and we don't have 5 year plans today - and that's a good thing by the way.*"

To which R43 adds:

> *"…we know that's not going to happen from the government. But that sort of number doesn't frighten big investors…And If you multiply that by 20-30-50 giga plants, that is what is the reality and we would be sensible of have 1 or 2 in Scandinavia. 1 in west coast of Denmark, one somewhere here and one in Norway to satisfy the EV needs"*

The supply capacity, or lack of, has already impacted industry which arguably was not expecting EVs to become popular in such a short time frame as R217, a Norwegian expert from a leading OEM, mentions:

> *"I can promise you the first time we were giving our estimates to factory, they were saying 'are you mad? Are you completely mad?' They would never believe that we would estimate so many cars."*

Respondent R057 further elaborates on the limitations of the supply of components for batteries, which might limit the eventual mass deployment of EVs in society. This is a point towards the diversification of power trains, not referring to society needing ICEVs, but rather other clean technologies such as hydrogen-fuelled vehicles.

> *"…we can't all go electric either. Because if in 30 years if everyone is electric, there is not only the energy supply but there is a constraint on the components that also use rare metals. So the best option is to have a range of good renewables but different kinds. Hydrogen might also start to become something, so that there is a mix. A big issue is when a mass goes for one thing because then everyone needs and wants it. From an environmental point of view, it is best to have a range."*

To which an expert from a traditional OEM mentioned that some brands are in fact ready for EVs and indeed have planned the transition for years, to launch their all-electric vehicles when the market is ready, which is now. For example, R57 argues that the car industry is changing, and their company has been preparing for such a change over the last several years:

> *"What also shows that we are serious about this is that in the car industry you have a platform, that is what you build your car on, and this platform dictates how big or wide the car is and how you can make the interior and space and where you draw your cables. Our platforms are ready made for full electric. So they can either be combustion or fully electric without compromising on interior or luggage space. So that shows we are ready. When the market is there, we are ready to go. We are that many years in preparation. It's not like a phone or cycles with 7 years. It is many years in the making, we have seen it coming for a while and are prepared."*

Therefore, it appears that some manufacturers have started and are making the supply chain modifications that are tailored for EVs. As another expert from a different leading OEM mentions, their brand will roll-out a modular platform to delivery several types of EV models for different car segments:

> *"But, from our side, 2019 production it will be from a completely new platform. The module for electric, yeah. And that will facilitate all these new models coming from this new EV platform."*

4.1.3.4 Charging concerns

While the above challenges essentially relate to the production of EVs, another challenge affecting the EV business case transition can be found in respect to the its recharging infrastructure, public charging stations in particular. These, are desired by consumers in an effort to mitigate their range anxiety and are just plain necessary for inter-city mobility. Hence, the forth element most commonly discussed by experts when talking about the EV business case issues was the charging infrastructure network. There are many questions around EV charging, from types of charger, speed of charging, availability and so on. Here, however, we focus on elements of ownership and responsibility and the role of different actors regarding EV charging infrastructure, as well as the expert's expressed lack of a suitable business model.

In our study interviewed experts begin with the question of ownership and responsibility, as there is uncertainty and controversy on who should lead (and pay) for the deployment of charging points across different region, as R014 elaborated:

> *"…the business concept its quite complicated for all [EV] infrastructure for example. Government doesn't know their role, energy companies don't know their role and the oil companies don't know their role. The question is how should build this [charging] plugs."*

To which the responded added that from the businesses perspective, and following the above discussed 'money talks' mentality of the industry, it should be governments leading the charging networks not the energy or automotive industries. Particularly, as it is governments that are striving for decarbonisation, and the business case of EVSEs is too weak for private companies to take the lead in developing such infrastructure:

> *"the energy companies are wondering is it our responsibility to build them? shouldn't the government participate? Because it's the government that wants to get rid of importation of fossil fuels, as you participate either with grand funding or some basic funding. So that's the kind of difficulty of who would do what?"*

Additionally, when one looks at the roles of ownership and responsibility of EV charging networks, subsequent questions arise regarding the actors that are involved on developing such infrastructure. From natural players such as EVSE providers, power utilities and public bodies, to others that may appear not related to electric mobility, but are a main driver of the competing the ICEV market. This in turn brought some experts to discuss another industry player in their role of the current ICEV automotive regime and its place in an electric mobility market: the oil sector, which currently supports the fuelling of conventional vehicles. In this way R014 adds:

> *"but oil companies don't know what to do, what business is it for them?"*

Inherently one could consider that oil companies do not have much of a role in transitioning to EVs, apart from contributing to continue to better the ICEV business case and supports its refuelling networks. However, even on this space some traditional oil players have started to place EVSE on existing refuelling stations, and even some have acquired EVSE businesses such as Shell has done with New Motion(Katakey 2017).

While there is uncertainty on who should lead the wide-scale implementation of a charging network and also on what is the role of existing players that support re-fuelling ICEV stations, there are many different business models for charging infrastructure already rolled out for different segments. However, the level of success of these is questioned by experts with no clear model that is scalable and profitable. In this way, R055 mentions that initially the model has been to not charge for the actual use of public chargers:

> *"Yeah there are a lot of different ones. In the cities, normally you pay for the parking. Like Stockholm, Stockholm Parking Company, they don't charge an extra for the use of the charging for public use."*

The free access to public charging has been used to promote EVs in most countries, but experts recognise that is a model that is not sustainable and municipalities and public charging owners will begin to charge for their use:

> *"…then they have to pay for the electricity and the use of that charger station. But when we will start this business next year, everybody will have to pay also for the use of the charging system."*

Thus, the EV market will not only introduce prices to public charging, but depending on the type of charger, the introduced prices will be set at different levels according to for example the speed of charging. This with the aim to mitigate the high costs of such infrastructure, as R059 elaborates that fast-charging stations requires high pricing due to their high investment costs. However, there is no established model for charging, whether this is at home, work of at a public space, as the respondent continues to elaborate that in Sweden there is not an established norm yet, with some players still providing the service for free:

> *"That's our business model. But it varies very much. And also I mean the fast charging stations, normally you pay for using them of course. Since investments are high. But it varies, I've also seen Malmo parking company, they don't charge anything extra today either. Not today."*

Notably, though, the respondent remarks the importance to develop suitable EV charging business models because the variability in type of models currently creates deterrents for EV adoption. This by noting that it is industry and government that, through the uncertainty with charging networks, create messages to consumers that deter EV adoption. Both by creating uncertainty for consumer on what to expect for re-charging stations –if these are free of use, for how long, or how high will the eventual price per kWh be –and also contributing to the general idea that electric vehicles are expensive:

> *"…and then there was a lot of debate, are the utility companies, governmentally owned, Vattenfall and so on, should they actually take a price, giving the signal to the society that don't buy an electric vehicle because it is very expensive, and so on."*

However, the current reality is that charging networks are limited in most regions, both in the total number of EVSE available and also in the EVSE per vehicle. Table 19 shows the total number of EVSEs per country and how these compare against national EV fleets and also total vehicle fleets.

	<22kv EVSE[a]	>22kv EVSE[a] (fast chargers)	Total EVSE[a]	EVs per EVSE[a]	~Total vehicle fleet	EVSE% of total vehicle fleet[g]
Denmark	2124	492	2,616	5	3,037,687[b]	0.09%
Finland	706	259	965	10	2,692,785[c]	0.04%
Iceland	40	87	127	57	344.664[d]	0.04%
Norway	8774	2421	11,195	19	2,719,395[e]	0.41%
Sweden	2731	5493	8,224	12	4,845,609[f]	0.17%

Table 19. EVSE stations in the Nordic countries 2018. Source**:** (a) European Alternative Fuel Association, (b) Statistics Denmark, (c) Statistics Finalnd, (d) Iceland Monitor, (e) Statistics Norway, (f) Official Statistics of Sweden, (g) authors.

The low levels of EVSE experts mention, reflects the hesitancy of industry players and governments to lead a large-scale rollout and it is due to the uncertainty of recapturing the investment returns. R49 puts it in simple words comparing it to current ICEV stations:

> *"Just like a petrol station, they don't exist because the authorities tell them [petrol and gasoline suppliers], they exist because they want to make money."*

To which R014 further highlights the lack of business case for charging infrastructure and the current only business that results from them is for utility companies that can subsequently charge for additional electricity used by EV users at home or at work:

> *"There's no [current] business case in it, because how much are you going to charge to be able to pay back the investment cost of the infrastructure, so you're losing money, so you're using it as a market tool or it's the utilities that own the plugs and they lose the money at the plugs an then they earn the money back when I charge at home or at work, when I'm actually buying the electricity from them."*

The flaws on the existing business case for a public charging market are the result of two main elements of the business model: the lack of volume of customers and the potential high prices companies would need to charge customers. As R076 mentions:

> *"…it's a large amount of vehicle that is needed in order to make public charging worthwhile or profitable."*

And R075 adds:

> *"…several of the companies charge up to, almost up to 1 euro per kWh when you charge along the highway and very few people are willing to pay that."*

The acknowledgement of the lack of a business model for charging infrastructure was consistent across experts, as R054 agreed:

> *"…there's no business model around this yet."*

Nonetheless, experts also pointed that, just as with the supply chain models, EVs need tailored solutions for charging network models, and that in particular for home and work charging there is no need of a model itself, as R075 adds:

> *"There is not [a current business model], and in terms of housing there does not have to be."*

This, considering that most of EV charging occurs at home or at work, and therefore even when EVs become mainstream in society, there are going to be limited public charging business opportunities as R010 mentions:

> *"…you will charge at home probably 95-98% of the time, I think, so in reality the business of owning complete infrastructure and selling the car with access to the infrastructure, that idea becomes obsolete and its more about location of having the juice at the right location exactly when needed and sell it there for premium, that's more suited. You know you come down the mountain, and you come down and your car its empty and right at that spot you're willing to pay premium for the extra use of the car."*

This was corroborated by a charging infrastructure expert, R076, where the business of owning a public charging network is limited, and the industry's investments are a reflection of it. Moreover, it turns the focus to other models where extensive investments are not needed by single agent but rather the network is shared via roaming services.

> *"I mean, the more we roam the less we need to invest in infrastructure. The charging unit is expensive and we cannot see a return on that in any kind of reasonably time. So, we try to invest as little as possible. But we do invest. As I said we invest where we don't have partners and we see that our partners expect us that we have chargers, so that we have a full coverage for Sweden and Norway."*

Thus, from a business perspective the lack of charging infrastructure experts suggest is due to the lack of a profitable business model that would allow to recapture the hefty infrastructure investments. This opens questions regarding roles and responsibility of ownership, considering there is currently not a business case behind it. However, while a public charging business model is necessary for inter-city mobility and address issues such as range anxiety, EV charging is expected to mostly occur at home and work places and therefore the business focus may turn to these locations. Particularly as EVSE owners would find the necessary volume and the certainty of charging at these locations.

4.1.4. Discussion: Recalibrating business models for electric mobility

Currently, despite all of their proclaimed promise and hype, our evidence suggests that electric vehicles face unfavourable market conditions, led in particular by the legacy of the petrol and diesel car industries, as well as regulatory and policy frameworks that continue to support those industries and their products. Our findings show that the lack of a business case is a result of an unsuitable business model and supply chain that does not optimise the production and delivery of electric vehicles to automotive consumers. This create deterrents on both the demand side, with only a few overly-priced vehicle offerings, and on the supply side, with an unprofitable product that also damages nested investments from ICEV product lines and support networks. For industry, the development of EVs particularly affects the selling methods (i.e. dealerships), component manufacturers, maintenance networks (and revenue streams) and refuelling (recharging) networks. Moreover, the development of EVs also brings business questions in terms of scalability and sustainability of production lines, which is mainly related to the capacity of industry to meet production demand, as well as develop the support networks around EVs, if these are set to become mainstream in society.

Therefore, new business structures need to be created to fit EVs and optimise their production and market delivery. These business models for EVs must fit within, or at least not entirely disrupt, automotive industry's structure and method of selling cars. On the production side of EVs, our results show that the lack of profitability comes from unsuitable assembly lines. These can be attributed to the lack of investment on EV technology, as OEMs are trying to protect their ICEVs investments, and also because EVs are assembled under the same structures as ICEVs of today. Such strategy makes the production of EVs inefficient and not suited for its characteristics, such as less movable parts and arguably simpler assembly process, which calls for its own bespoke modular chain that optimises the interior space and weight of each design as well as the operational process of production. Our results also show that two of the interviewed OEMs expressed the implementation of this modular approach to be launched as early as 2019, which would result in a decrease in production EVs costs, therefore directly bettering their profitability and affordability.

Moreover, EVs directly affect the existing ICEV business structures by almost eliminating the volume of work from maintenance business units, as shown in our results. For this reason, a potential new model for EV sales is to reduce or even remove the unit of car dealerships from the automotive selling chain. Tesla is well known for entering the industry with a business model that uses dedicated showrooms, more for branding and positioning, with specialised sellers that act more as product consultants, instead of a large-scale network of dealerships on every location. To this end, our respondent R36 (below) takes this concept further and mentions the EV model should lose entirely its dealership model, and even showrooms, to help reduce dramatically the costs per EV unit. This model would help EVs to become more profitable for OEMs, be more accessible for consumers, and also fit the nowadays automotive purchasing trend where, as R022 mentioned, most of the purchasing decisions are made from peer-to-peer information and online research before any actual engagement with dealerships:

> *"So we basically skipped the cost of having to have huge [selling units] like all this dealerships today. Yea, they are huge, with a lot of people working and a lot of cars inside. All this, it's gone. So, it will be like Amazon for cars, so that's why you get price of cars much lower than if you go and buy it."*

Admittedly, eliminating entirely the dealership model can be challenging, considering the dependencies the system creates such as local investments (warehousing or product-stocking), and employment. Alternatively, to increase sales, EVs business models can be fitted to the benefits but also limitations of the technology, for example when referring to matching real EV driving range with expected consumer driving range. This is explained by respondent R051:

> *"Swedes are choosing their car for 5% of their usage. The 5% rule I call it. Because in 5% of the cases they need the station wagon, because they need to pack and so on, and they need the toe hitch for caravan, and 4-wheel drive because of the weather. 4-wheel drive today its very common, but it's used 5% [of the time]. The other 95% you use the car to go to work, to go to day-care, shopping and you don't need it. But with another business model could you find a way to cover those 5%, so that you could actually drive a Nissan Leaf 95% [of the time] and when you need the toe hitch, perhaps you can turn your car to the dealership, they wash it, you can borrow a large pick up, and that's free of charge. So that's the business model."*

This model would require a way to deal with the potential peaks in demands during holiday weekends, and the potential other uses a SUV-pickup truck fleet could have when not used. However, in principle it can help remove the mental range anxiety barrier around EVs. Moreover, in creating avenues for EV access to consumers, a leasing model needs to be commercially available for private consumers as, R062 mentioned, there is currently a lack, or no offerings, of this kind for EVs. This model can take advantage of the fast-changing technological nature of electric cars and mitigate two current expressed barriers for adoption: high purchase prices and battery concerns. Within an EV leasing model, returned cars can be refurbished with newer and better batteries, to then be either given back to the leasing customer or make it available to the wider market. While the removed batteries can be re-used as part of stationary storage solutions for demand response and power balancing. This model was supported by experts, such as R114 of a major OEM:

> *"…you can opt for buying the first version with a sixty amp [battery], and you can buy the new battery package, increasing range. So just the thought for the future, when we get our used EV car back, say you strip it for battery and you install a new battery and you push into the market again, with a same car, same driveline but a new battery with increased range."*

Through this leasing option is where sellers can further incorporate and levy the costs of charging infrastructure networks, via subscription services depending on a range of access to charging point or volume of driving. There are some players already moving into this space, either in a Tesla-like model where, as expressed by R075, the cost of charging is included on the premium vehicle prices. Alternatively, other have formed partnerships between charging providers and automotive brands for a home-charging package for EV sales, and thus this model can be made available for leasing options. R075 continues to elaborate:

> *"…including it [the cost of charging] in the pricing of either the car or your annual electric bill for your housing is I think the way forward here."*

In dealing with the lack of EV volume to support their business case and the development of a charging network, an EV model can adopt its selling method by targeting mass adoption of public bodies, and initial market entry point. This is for example, a case in Denmark, and rather successful considering the significant market barriers for EVs at a retail level. Here OEM brands have targeted municipalities to increase visibility, presence and eventual sales of EVs, as R114 explains:

> *"When you're in the car business, you know cars sell cars. When you see cars in the street, people see them and they want it. EVs, were not out there yet. We have Teslas but that's it. So we kind of thought, ok if we, let's spend 50 hours on EVs selling, we could spend 50 hours selling EVs to normal people, and you might be lucky to sell 10. We [instead] focus on municipalities that have a political agenda saying they want [EVs] and we might be able to sell 500."*

While this method also faces limitations from public bodies budget constraints and sustainable aspirations, it has the potential to reduce operational costs, time spent in selling EVs, and in optimise EVs selling potential, both with more EVs on the streets and encouraging prospective sales.

4.1.5. Conclusion & Policy Recommendations

In sum, this paper has shown that the reasons for an inferior EV business case are arguably straight forward, as identified by our expert interviewees. With an industry that is trying to protect their ICEV investments, a lack of suitable business models, practices and production methods tailored for EVs, and lack of government support for the technology; all impeding EV adoption on the supply side and the demand side. In combination, these elements have to date tempered with EV adoption creating an unprofitable product for industry to sell and overly-priced vehicles for consumers to buy.

These symptoms would appear to be a result of the legacy of the ICEV market and could be organically overcome in time as the EV market progresses. However, as noted by experts, a key aspect of the industry it's the long lead times to deliver products and considering EVs are indented to be used as a tool for decarbonisation, the speed of the transition has to be accelerated. To do so, both industry and government have to continue to innovate their strategies, planning and models to optimise the delivery of EVs to the automotive market. On this paper we have shown avenues for this purpose, such as optimising EV production and selling methods, to create a profitable product for industry and an accessible one for consumers. In this way EVs could move from their current limited market segment into the mainstream.

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4.2 Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark

The sixth article presented on this dissertation (second of this theme) looks into the social costs and benefits of potential configurations of electric vehicle deployment, including and excluding vehicle-to-grid. To fully explore the benefits and costs of different electric vehicle pathways, four different scenarios are devised with both today's and 2030 electricity grid in Denmark. These scenarios combine different levels of electric vehicle implementation and communication ability, i.e. smart charging or full bi-directionality, and then paired with different levels of future renewable energy implementation. Then, the societal costs of all scenarios are calculated, including carbon and health externalities to find the least-cost mix of electric vehicles for society. The most cost-effective penetration of electric vehicles in the near future is found to be 27%, increasing to 75% by 2030. This would equate to a $34 billion reduction to societal costs in 2030, a decrease of 30% compared to business as usual. This represents a projected annual savings per vehicle of $1,200 in 2030. However, current vehicle capital cost differences, a lack of willingness to pay for electric vehicles, and consumer discount rates are substantial barriers to electric vehicle deployment in Denmark in the near term.

4.2.1. Introduction

The general benefits of electric vehicles (EVs) are well-documented in the literature on transport and energy policy. For example, it has been estimated that gasoline combustion for passenger vehicles causes $26 billion in health damages annually (von Stackelberg et al. 2013) Likewise, EVs are an integral part of modelling of systems with the aim of complete carbon emission mitigation (Jacobson et al. 2013). In combination with renewable electricity, many studies have found the large-scale de-carbonization transition to be cost optimal, especially including electrification of heat and transport (Budischak et al. 2013). Moreover, EVs have the ability to provide storage to intermittent renewable electricity sources, using vehicle-to-grid (V2G) technology (Kempton & Tomić 2005b; Budischak et al. 2013). However, these previous studies utilize computationally intensive models, which limit their resolution (i.e. they only model every 5% EV penetration), as well as their technologies of choice. As such, many large-scale renewable energy models do not include V2G-capable (or any kind of) EVs (MacDonald et al. 2016; Mai et al. 2014; Elliston et al. 2013). Many others include only a cursory look at the interaction between EVs and renewable energy (Delucchi & Jacobson 2013; Noel et al. 2017; Budischak et al. 2013; Lund & Kempton 2008). This paper aims to more comprehensively explore the role of EVs and renewable energy to supplement larger socioeconomic studies that aim to model complex interactions between renewable energy and electrification of transport, using Denmark as a case study Denmark offers an illustrative case study as its primary transport and energy challenges, like most European countries, centre on decarbonization and electrification (Benjamin K.

Sovacool, Kester, et al. 2018), and Denmark also can provide a laboratory of real world experience related to EV and V2G diffusion (Kester et al. 2018b).

Granted, there has been a plethora of studies that investigated the integration of electric vehicles into the electric power system, particularly from a technical (as opposed to socioeconomic) perspective of grid impacts and renewable energy integration (Richardson 2013). Indeed, most of the recent literature tends to not compare different levels of communication ability (i.e., non-controlled or random charging, often called "dumb charging," vs. controlled charging, known as "smart charging" or V1G, vs V2G), and usually does not calculate societal costs nor cost optimize, and instead focuses exclusively on the grid's performance. For example, a recent paper found that increasing levels of EV penetration would increase renewable energy utilization and reduce carbon emissions in Croatia (Novosel et al. 2015), but did not cost optimize nor discuss V1G/V2G. Other papers have found that the technical impacts of EV grid integration are potentially negative (Lopes et al. 2011; Drude et al. 2014), but could provide benefits with market formation and communication.

Another common topic was how EV integration influences renewable energy usage (Atia & Yamada 2015; Bellekom et al. 2012), but these papers tend not to calculate total societal costs. In this thread, Forrest et al. modelled various combinations of renewable energy penetration and combinations of dumb charging, V1G and V2G communication ability, finding that V2G can completely obviate the need for secondary stationary storage to reach high renewable energy levels (Forrest et al. 2016) (but only modelled certain combinations of EVs and renewables, and did not calculate any cost-related metrics). Those that did include cost in their calculation did not compare costs between all the possible charging scenarios, and took comparatively narrow approaches to cost. For example, Kara et al. finds that implementation of V1G can reduce a consumer's monthly bill by about 25%, largely due to reductions in maximum demand (Kara et al. 2015); though this paper does not include V2G, nor cost optimizes across all possible penetrations. Next, Graabak et al. modelled the impact of 100% EV penetration on the Nordic region transmission grid and compares dumb and V1G charging strategy's, finding that V1G can greatly decrease requisite investment in Nordic transmission upgrades while maximizing electricity-grid related welfare (Graabak et al. 2016). Some, such as Seddig et al, compared both renewable energy integration and consumer cost, and found that that V1G charging increases renewable energy utilization and reduces consumer costs (Seddig et al. 2017). Most comprehensively, Ekman compared dumb, V1G, and V2G communication and found that electrification of transport and increased communication has a positive impact on renewable energy utilization in Denmark (Ekman 2011), but did not present the societal cost-benefit across different levels of implementation.

As compared to the existing literature, this work aims to make four novel contributions. First and foremost, the model here introduces comprehensive socioeconomic cost-optimization for all levels of EV penetration, with and without externalities. Secondly, the results show both the specific societal cost-benefits and renewable energy integration benefits between dumb charging, V1G, and V2G. Thirdly, this paper includes a more realistic cost of EV deployment, using a WTP cost premium, instead of assuming there is no cost (and also no transportation-related benefit) of switching from ICEVs to EVs. Fourthly, the results also show the role that the future integration of wind and reduction of battery prices has on the overall cost optimized EV penetration, as well as the necessity of EV communication. The model and results are presented for the three scenarios (Dumb, V1G and V2G) in Danish power system exclusively between 2015-2030, the end date of 2030 corresponding with national policy targets for a carbon-free electricity sector (Sovacool 2017).

4.2.2. Research Methods: Modelling, Data Collection, and Cost Calculation

As our primary method, an iterative model was developed that calculates the costs of transportation and electricity for each percent of EV implementation, i.e. 1% to 100% of total vehicles in Denmark are electrified, under each of the three scenarios. As a baseline, the total costs of the system assuming minimal EV implementation, i.e., 1% penetration was calculated. Next, the costs and benefits of "Dumb" EVs were calculated, meaning the EVs have no communication ability, and charge blindly, which largely reflects current practices. Secondly, the costs of EV implementation assuming one-way communication ("V1G") that facilitates so-called "smart charging" were calculated. Essentially, this allows the EVs to shift demand over the day to when renewable electricity production is highest. Lastly, the costs and benefits of EVs assuming full communication and power bi-directionality were calculated, termed as "V2G". While there are many benefits of V2G EVs, such as participation in the frequency regulation, spinning reserves, and other markets (many of which are not even developed yet), the model only calculates the benefits of V2G providing storage for excess renewable electricity, and decreasing dispatched conventional electricity, and the existing ancillary services market. For each of these various scenarios, the model calculated the net present cost over a lifetime of 25 years, see section 2.3 below.

4.2.2.1 Model Description

For each of the above-mentioned scenarios, the Danish electricity grid was modelled, based on 2015 hourly load, 2015 hourly actual wind and solar production (Energinet.dk 2016), and estimated charging profiles, based on an EU study (Pasaoglu et al. 2013). All modelling was conducted in MATLAB using scripts written by the authors. For each percentage point of EV implementation, the additional load from EV charging was modelled on the electricity system at each hour for the year 2015, based on an aggregated charging profile. For the "Dumb" EV scenario, it was assumed that the charging profile could not be shifted. If that specific hour had excess renewable generation, then the additional EV load could be met through renewable energy – otherwise, the system would necessitate increased conventional generation, or if already at maximum capacity, the construction of new combined heat and power (CHP) natural gas plants to meet this load. See Figure 14. For both the V1G and V2G scenarios, the difference in the *total* daily EV load and excess renewable generation was calculated, in order to estimate the benefit of the EVs being able to shift load throughout the day. If the daily EV load exceeded the amount of renewable generation throughout the day, this additional load was proportionally allocated throughout the day in order to reduce the maximum conventional, and likewise reduce the need to build new natural gas plants. Finally, in the V2G scenario, the model also allowed for the possibility of V2G storing the excess renewable electricity to displace both new and current conventional generation (assuming EV load had already been met). In addition, as discussed above, V2G currently participates in ancillary services (Benjamin K. Sovacool, Noel, Axsen, et al. 2018), and the model includes the cost-benefits of participation as V2G capacity increased, with aggregator costs removed. At the end of the year, the model calculates the required new capacity to be built, as well as the energy distributed into current conventional generation, renewable generation, and new natural gas generation. Based on these results, the model then calculates the net present cost over 25 years (the usual life-span of an electricity generation plant (Lazard 2017)) for each of the various scenarios and combinations of EV penetration.

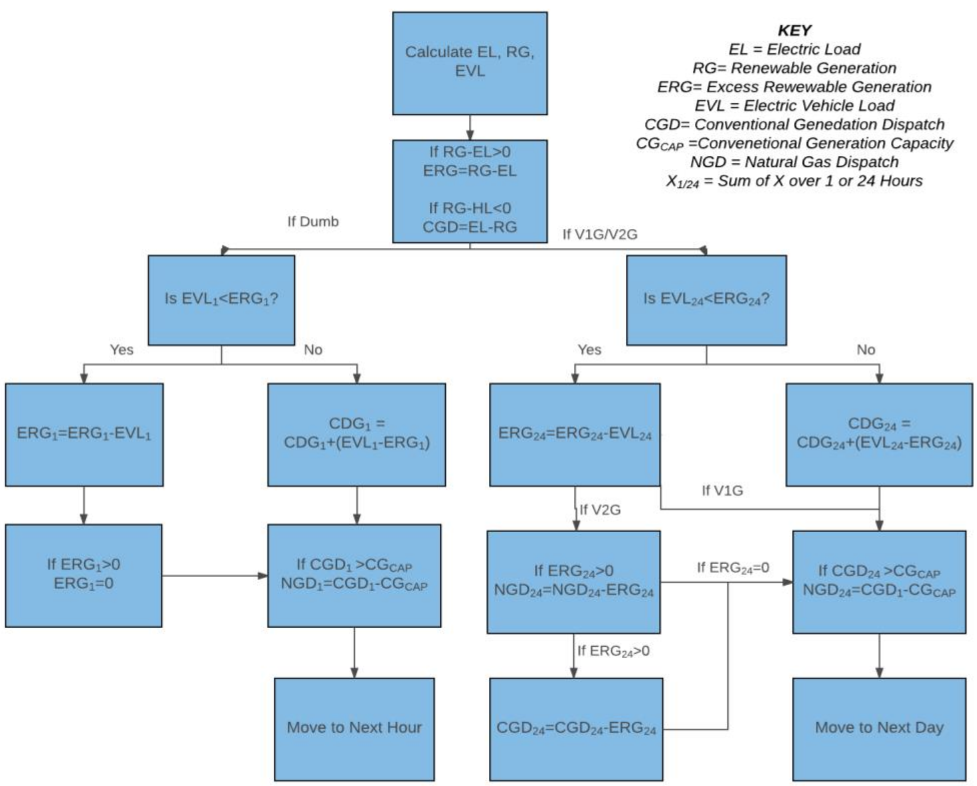

Figure 14. Hourly Operation of Modeled EV Integration in the Electricity Grid with Various Communication Scenarios. Note: Constructed by authors.

4.2.2.2 Data Collection

The model is based on collecting several inputs for cost and other technical parameters from a review of the current literature. See Table 20 for a summary of the data utilized by the model. The data collected can be broken into three categories; costs related to EVs, costs related to internal combustion engine vehicles (ICEVs), and costs related to the electricity system.

a) Electric Vehicle Related costs

EVs have several costs to society as EV penetration increases. First and foremost, the primary cost of EVs is the potentially higher capital cost when compared to a typical ICEV. However, due to the relative novelty of EVs, the switch from an ICEV to an EV would require either a behaviour change to adapt to a lesser driving range (at no additional, and perhaps a lower capital cost) or a substantially more expensive EV that has a range similar to current ICEVs (e.g. a Tesla Model S). This choice depends on individual characteristics and decisions and is heterogeneous across the Danish population. To capture the variation of individual's willingness to purchase an EV, recent willingness-to-pay (WTP) was used that allowed differentiation of WTP across a population (Hidrue et al. 2011). The stated WTP was then added, or in some cases subtracted, from the estimated cost of an EV to see what the "true" societal capital cost would be, as shown in Equation 2. Then, the model calculates the difference between this adjusted EV capital cost and the average capital cost of a comparable ICEV vehicle within the same class, based on average sales in Denmark (Statistics Denmark 2016) (EA Energy Analyses 2015), with taxes removed, for each percentage point of the Danish population. One should note that, with taxes excluded, an average small ICEV car in Denmark can cost as little as $8,500, and Denmark has had historically the cheapest ICEVs within the EU when excluding taxes (European Commission 2011). For more information, see the Appendix. To estimate future differences between EV and ICEV capital costs, battery cost was adjusted in Equation 2 based on estimated future decreases to battery prices (Knupfer et al. 2017), based on innovation and technological learning, in turn decreasing the cost difference between ICEVs and EVs.

$$EV\_Cap_{ijy} = \left((k * BC_y * S_j) - ICEV_j\right) - WTP_{i,j}$$

	EV_Cap		Capital Cost to Incentivize Person i to Purchase EV_j (in $/car)
	k		Estimated Proportion of Battery of Total Electric Vehicle Cost
	BC		Cost of Battery (in $/kWh)
Where	ICEV	*equals*	Average Gasoline/Diesel Vehicle Cost (in $)
	WTP		Stated WTP (in $)
	S		Size of Battery (in kWh)
	y		Year

Equation 2. Estimated Cost of Electric Vehicle j for person i.

Next, the second cost associated with EV implementation is the charger, also known as the electric vehicle supply equipment (EVSE). It was assumed for each EV there would be two EVSE's - one at home, and one public – while the optimal mix of EVSE was assumed to be 90% level 2 AC (at home and at work) and 10% public level 3 DC (Zhang et al. 2013). The AC EVSE cost $3,000, and the level 3 DC charger $30,000, based on estimates from the literature (Kempton et al. 2014; Yilmaz & Krein 2013; Schroeder & Traber 2012).

Thirdly, one advantage of the EV is decreased maintenance cost in comparison to an ICEV, as result of the reduction of moving parts. Thus, for every vehicle that was modelled to switch from an ICEV to an EV there would be a yearly benefit to society in a reduction of maintenance cost. This cost differential, while not completely understood due to the youth of the EV industry, was estimated based on the literature (EA Energy Analyses 2015), which found such benefit to be $280 per year.

Finally, the fourth cost associated with EVs is the additional electricity load as result of charging batteries from driving. To accurately model the additional load, the model calculates an hourly charging profile per average individual EV, based on a recent report on load profiles (inclusive of driving and parking patterns) (Pasaoglu et al. 2013). This hourly charging profile was then scaled up, depending on the total amount of EVs modelled, and then added to the total electricity load. The costs of this additional load to the electricity system, and potential increases in externalities due to EV charging is described below in Section 4.2.2.3.

b) Internal Combustion Engine Vehicle Related Costs

Conversely, there are various societal costs associated with the continued use of gasoline and diesel in ICEVs. Unlike EVs, it was assumed that there would be no capital costs associated with ICEVs, as the Danish population already had purchased ICEVs, and the counterfactual would be continued ICEV operation. However, for every vehicle that remains an ICEV, there are several costs to society, namely; fuel costs, health costs, and climate change emissions.

To estimate the fuel costs, first the average mileage efficiency of ICEVs was calculated, which was based on a recent Danish transport study, modelled for various types of vehicles for the years 2015 and 2030 (EA Energy Analyses 2015). Based on this report, average gasoline ICEVs will achieve 18 km/l in 2015 and will increase to 26.5 km/l by 2030, and the average diesel ICEV will achieve 20.3 km/l in 2015, increasing to 27.6 lm/l by 2030 (28). The total average annual kilometres driven per car based on average daily distances driven was calculated (Pasaoglu et al. 2012), and then divided by the average mile efficiency to find total annual gasoline consumption. Next, this was multiplied by the current average gasoline prices, with taxes excluded (EOF 2016).

To account for the natural increase in gasoline prices, the cost of gasoline was then increased, based a recent EIA report on global oil barrel prices, increasing from a current $50 per barrel to just about $100 per barrel (IEA 2015).

c) Externality costs (air pollution and climate change)

In the scenarios that include externalities, the damages associate with particulate matter emissions from the combustion of gasoline were monetized. This was calculated based on a health-cost analysis done specifically for Danish ICEV emissions and their impacts on Denmark and the neighbouring European Union (Brandt et al. 2011). This was then scaled up or down based on the amount of gasoline consumed (Anon 2015). Likewise, gasoline also emits climate change inducing gases. The carbon content of gasoline was obtained from the EIA, and then converted into metric tons per litre for both gasoline and diesel (EIA 2016). These were then converted into monetary damages by multiplying these contents by a social cost of carbon, which increased from $41 per ton of CO_2 in 2015 to $58 per ton by 2030, based on a recent comprehensive report on the social cost of carbon (Interagency Working Group on the Social Cost of Carbon 2013).

d) Grid Integration Costs

Finally, the cost of the Danish electricity system was also calculated. Similar to the way the model treated ICEVs, the capital cost for the existing electricity system was not included. However, given that the Danish electricity system is expected to change rapidly over the next 15 years, with the amount of annual wind generation practically doubling (Energinet.dk 2013). Because the installation of wind and solar plants would occur regardless of the type of vehicles driven, the model did not include the capital costs of new capacity additions. However, if the additional load due to charging demand caused load to be greater than the available hourly capacity, then the model built new natural gas plants exclusively for providing electricity for this purpose. If built, then the cost of the requisite capacity was calculated, using the capital cost for new natural gas plants, based on the literature (World Energy Council 2013).

Next, the model calculated the hourly fuel and maintenance cost for both existing generation and new natural gas plants (Danish Energy Agency 2015). One of the main benefits of the “smart” EVs (the V1G and V2G scenarios) is that they can be controlled and store electricity to maximize use of renewable energy, implying the introduction of “smart” EVs can reduce electricity system costs. The model accounts for this by calculating total annual electricity fuel and maintenance cost for each iteration of EVs. Likewise, the model also calculated the health costs associated with combustion of both coal and natural gas, based on the impacts of particulate matter on Denmark and the neighbouring European Union (Brandt et al. 2011), updated for the current fuel mix in Denmark (Anon 2015). Likewise, carbon emissions associated with coal and natural gas were estimated based on carbon content and the social cost of carbon (Moomaw et al. 2011), (Interagency Working Group on the Social Cost of Carbon 2013). It should be noted that the additional societal costs of conventional generation to meet increased EV charging load are included in these calculations. Similar to fuel and maintenance cost, total annual health and carbon costs were calculated for each system to estimate the societal electricity system benefit of V1G and V2G EVs.

Variable	**Value**	**Citation**
Total Vehicles in Denmark	2.26 Million (in 2015) 3 Million (by 2030)	(Dargay et al. 2007)
Total Annual Distance Driven	14,600 km/year	(Liu et al. 2015)
EV WTP Capital Cost Premium	-$1,300 -$27,000/car	(Hidrue et al. 2011; Noel et al. 2017)
EVSE Capital Cost	$3,000 (for AC) $30,000 (for DC)	(Kempton et al. 2014; Yilmaz & Krein 2013; Schroeder & Traber 2012)
EV Battery Cost	$226/kWh (in 2015) $100/kWh (in 2030)	(Knupfer et al. 2017)
EV Annual Maintenance Benefit	$280/EV/year	(EA Energy Analyses 2015)
Petrol Efficiency	18 km/liter (2015) 26 km/liter (2030)	(EA Energy Analyses 2015)
Diesel Efficiency	20.3 km/liter (2015) 27.6 km/liter (2030)	(EA Energy Analyses 2015)
Gasoline Fuel Cost	$0.72/liter (2015) $1.31/liter (2030)	(EOF 2016)
Diesel Fuel Cost	$0.70/liter (2018 $1.31/liter (2030)	(EOF 2016) (EIA 2017)
Gasoline Carbon Cost	$0.11/liter (2015) $0.15/liter (2030)	(EIA 2016; Interagency Working Group on the Social Cost of Carbon 2013)
Gasoline Health Damages	$0.171/liter	(Brandt et al. 2011) (Anon 2015)
Current Conventional Electricity Capacity	8.2 GW	(Anon 2015)
Current Conventional Electricity Fuel Mix	80% Coal 20% Natural Gas	(Anon 2015)
Current Conventional Electricity Fuel Cost	$29.1/MWh	(Danish Energy Agency 2015)

Current Conventional Electricity O&M Cost	\$16.5/MWh	(Danish Energy Agency 2015)
Current Conventional Electricity Health Cost	\$19.6/MWh	(Brandt et al. 2011) (Anon 2015)
Current Conventional Electricity Carbon Cost	\$37.4/MWh (2015) \$52.0/MWh (2030)	(Moomaw et al. 2011; Interagency Working Group on the Social Cost of Carbon 2013)
New Natural Gas Capital Cost	\$978,000/MW	(World Energy Council 2013)
New Natural Gas Fuel Cost	\$56/MWh	(Danish Energy Agency 2015)
New Natural Gas O&M Cost	\$10.7/MWh	(Danish Energy Agency 2015)
New Natural Gas Health Cost	\$9.4/MWh	(Brandt et al. 2011) (Anon 2015)
New Natural Gas Carbon Cost	\$19.6/MWh (2015) \$27.3/MWh (2030)	(Moomaw et al. 2011; Interagency Working Group on the Social Cost of Carbon 2013)

Table 20. Model variable summary. Note: Constructed by authors.

4.4.2.3 Cost Calculation

For each iteration of EV penetration under each of the three modelled scenario, the total societal costs were calculated in net present value over a 25 year period, assuming a social discount rate of 3% (Interagency Working Group on the Social Cost of Carbon 2010; Interagency Working Group on the Social Cost of Carbon 2013). As described above, the total cost includes both transportation and electricity related costs due to EVs, and including and excluding externalities. See Equation 3.

$$Total\ Cost = EV \times EV_{CAP} + NNG_{MW} \times NNG_{CAP} + \sum_{i=1}^{25} \frac{EV \times EV\_O\&M_i + (ICEV_{GAL} \times (FuelCost_i + H_{GAS} + SCC_{GAS}) + ElecGen_{i,k} \times (VOM_k + H_k + SCC_k)}{(1+r)^i}$$

Where … *equals*

EV	Total Amount Electric Vehicles
EV_Cap	Capital Cost to Incentivize Purchase of EV_j (in \$/car)
NNG_{MW}	Requisite Capacity of New Natural Gas (MW)
NNG_{CAP}	Capital Cost a New Natural Gas Plant (\$/MW)
EV_O&M	EV Operation and Maintenance Benefit (\$/car/year)
$ICEV_{GAL}$	Total Annual Gasoline/Diesel Consumption (in litres)
FuelCost	Average Cost of Gasoline/Diesel (in \$/liter)
VOM	Variable Operation and Maintenance (in \$/MWh)

H	Health Damages ($/litter or $/MWh)
SCC	Social Cost of Carbon ($/liter or $/MWh)
ElecGen	Total Annual Electricity Generated (in MWh for generation type k)
r	Discount rate

For year i and electricity generation type k

Equation 3. Total 25 Year Net Present Cost Calculation.

4.2.3. Results: Examining Vehicle-to-Grid Scenario

For each of the three charging scenarios, the minimum cost penetrations of EVs were found for each year, both with and without externalities. Table 2 shows the minimum cost penetration with and without including externalities for the year 2015, with the three charging scenarios, and also depicts the costs of these EV penetrations. First, the optimal penetration of EVs excluding externalities range from 26% to 37%, depending on the level of communication. In spite of the comparatively cheap costs of ICEVs in Denmark the model shows that ignoring taxes, EVs should be adopted a much higher rate than they currently are. However, tax differences and consumer irrationality regarding discount rate may be major impediments, see section 4 below. Looking across the columns, Table 2 shows that surprisingly, increasing communication-capabilities likewise barely impacts the optimal penetration of EVs. Adding fully bi-directionality to make EVs V2G-capable only slightly increases the optimal penetration of EVs, and decreases total societal costs only very marginally. In the short term, the results imply that there is only very slight, albeit positive impacts on reducing total societal costs by furthering communications to full bi-directionality.

Next, there continues to be only small (though more noticeable) differences between the communication scenarios when including externalities in the cost function. Firstly, when comparing to market costs, the optimal penetration of EVs increases in all communication scenarios. The benefit of communication between Dumb and V1G scenarios is essentially nothing, though V2G increases the optimal EV penetration more noticeably. As Figure 15 shows below, the differentiation in cost for the three charging scenarios is not obvious until at least EV penetration over approximately 30% to 40%, though the differences are more noticeable in 2022 and 2030 (due to higher penetrations and thus utilization of renewable energy). Overall, the optimal penetration barely increases with communication ability, the total cost savings is likewise barely decreased, by less than 1% difference across the three charging scenarios. On the other hand, including externalities does incentivizes further EV penetration by an additional ~8-10%, though the total societal benefits of communication are slight, especially in the near term. All in all, assuming that society aims to mitigate health and climate change damages, then the near-term target for EV penetration in Denmark should be drastically increased to nearly 37%.

Next, using 2030 costs and expected increases in renewable energy in the Danish electricity system (the current 37% renewable share of load to the projected 73% in 2030), noticeably changes the results. The optimal penetration of EVs drastically increases in all scenarios, regardless of communication ability. However, adding communication abilities now markedly decreases costs while increasing optimal EV penetration, see Table 21. This is more noticeable in the cost difference between the Dumb scenario and V1G, where total costs are reduced by about 3%. In comparison, the cost savings of adding bidirectionality is only 1.8%. Thus, while V2G increases optimal EV penetration and further reduces cost, these benefits are only marginal. Nonetheless, compared to the low percentages of EV penetration found in 2015, the differentiation across the communication scenarios are positive and more evident. Next, including externalities further increases the optimal EV penetration, although they generally follow the same trends as the market cost scenario across the communication scenarios. Again, assuming society intends to mitigate health and climate change damages, the optimal goal for Denmark should be reaching 75% penetration of EVs by 2030.

	"Dumb" Scenario		**"V1G" Scenario**		**"V2G" Scenario**	
	Optimal EV Percentage	Total Costs ($bil)	Optimal EV Percentage	Total Costs ($bil)	Optimal EV Percentage	Total Costs ($bil)
Market Costs						
2015	26%	70.9	26%	70.8	27%	70.5
2030	57%	75.0	70%	72.7	71%	71.4
With Externalities						
2015	34%	85.3	34%	85.1	37%	84.8
2030	70%	83.9	75%	80.4	75%	79.0

Table 21. Summarizing Minimum-Cost EV Percentages and Net Present Cost for Years 2015 and 2030 including Market Costs and Externalities.

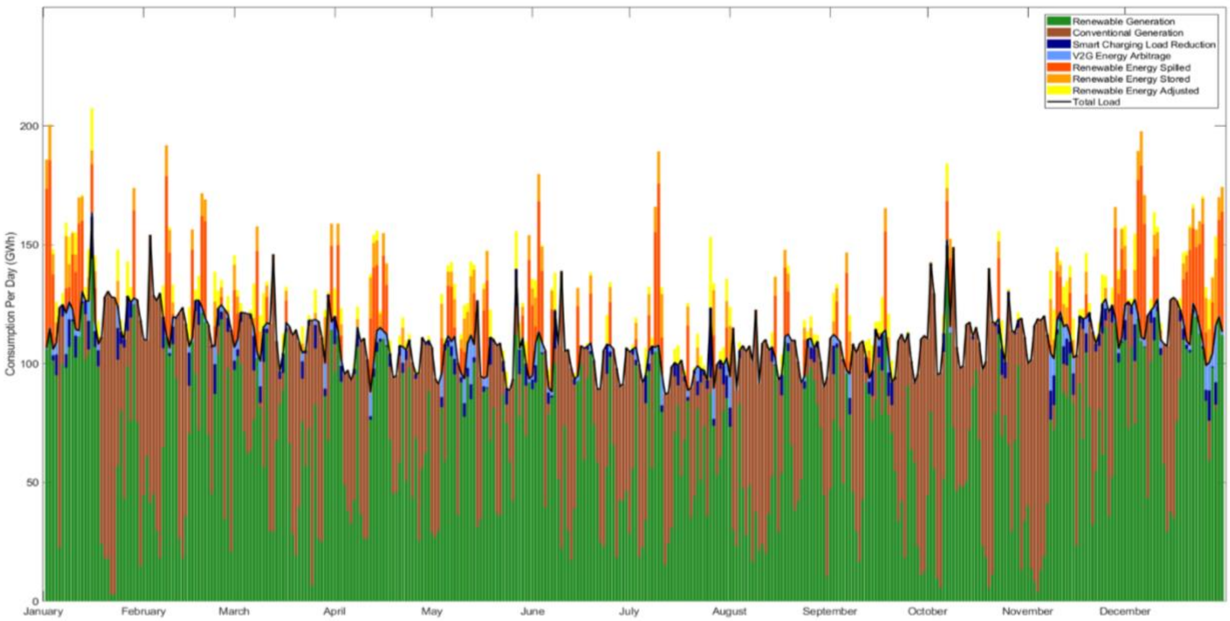

Figure 15. Daily Production, Consumption, Spillage Over Modeled Year of 2030 For 75% EV Penetration.

Figure 15 shows how the different capacities of each EV communication ability reduce the use of conventional generation (in brown in Figure 2) and increase the utilization of renewable generation (in green). Throughout the year, the amount that V1G smart charging and V2G energy arbitrage (shown in dark and light blue, respectively) decrease the total load (and thus conventional generation) is relatively moderate. To be precise, smart charging reduces load by 2.5% throughout the year, while V2G arbitrage reduces load by 4.1%. More importantly, V1G smart charging reduces conventional dispatch by nearly 7%, while V2G arbitrage reduces conventional dispatch by 10% over the course of the year. At the same time, the total amount of renewable generation spilled (shown in dark orange) is also decreased by V2G storage capacity (light orange), as well as shifting EV demand to match hourly renewable generation, which is termed as "renewable energy adjusted" (yellow). The impacts on renewable energy utilization is more dramatic, V1G smart charging decreases spilled renewable generation by 21%, and V2G storage decreases spilled renewable generation by 45% over the modelled year. However, given the moderate cost differences shown in Table 2, the marginal value of V2G over V1G in displacing the 3% conventional dispatch is relatively limited. Indeed, the value of V2G may be limited due to the model's restriction of using only intra-daily energy arbitrage for V2G. As shown in Figure 15, there are several times where there is a substantial amount of renewable generation spilled (red spikes above the load line) a few days before high amounts of conventional generation is dispatched. Looking towards future research, a key implication for V2G and renewable energy integration would be investigating the possibility of inter-day energy arbitrage of V2G and how driving demands would implicate long-term V2G storage. On the other hand, when the model added V2G and showed large reductions in renewable energy spillage, there was very minor economic value added, which may implicate the value of long-term V2G storage as well.

Figure 16 shows the total net present cost for each percentage EV penetration for the three charging scenarios (Dumb, V1G, and V2G), for the years (a) 2015, (b) 2022 and (c) 2030. First and foremost, these graphs show the cost difference between the three charging scenarios. Note that from 0-30% there is little cost differentiation between the level of communication available. However, beyond the 40% penetration of EVs there is a marked difference, especially between "Dumb" and either of the V1G or V2G scenarios. There is a very slight cost savings across all percentages of EV penetration for implementing V2G over V1G, which is due entirely to participating in ancillary services. When previous iterations of the model conducted analyses without the possibility of ancillary services, there was practically no cost difference between V1G and V2G, implying that energy arbitrage did not provide substantial societal cost savings, especially in the near-term. Next, across the three graphs, the slopes showing least-cost EV penetration appear to pass a threshold and become more dramatic, showing the substantial decreasing of costs as EVs become cheaper and renewable energy is more abundant. In fact, having no electric vehicles in the system goes from being, for all intents and purposes, nearly as inexpensive as the optimal penetration of EVs in 2015 to by nearly the most expensive choice by 2030. Due to the rapidly decreasing costs of batteries and potential threshold effects of reaching cost parity with ICEVs (even with current WTP cost premiums for EVs), the shift to EVs may occur rapidly. Indeed, in previous model runs, when an older battery cost was used ($325/kWh (DOE 2014), as opposed to $226/kWh (Knupfer et al. 2017)), the optimal EV penetration was found to be 0% in all charging scenarios cases. Finally, in all three graphs and communication scenarios, the cost of EV penetration above 80% substantially increases. One important aspect of this analysis that causes this exponential increase is the inclusion of WTP cost premiums for EVs, for which the final ten percent of drivers is prohibitively expensive. Thus, a barrier to complete electrification of transport will likely be some consumer resistance to the adoption of EVs, especially when considering many governments wish to completely phase-out the selling of ICEVs in the near future.

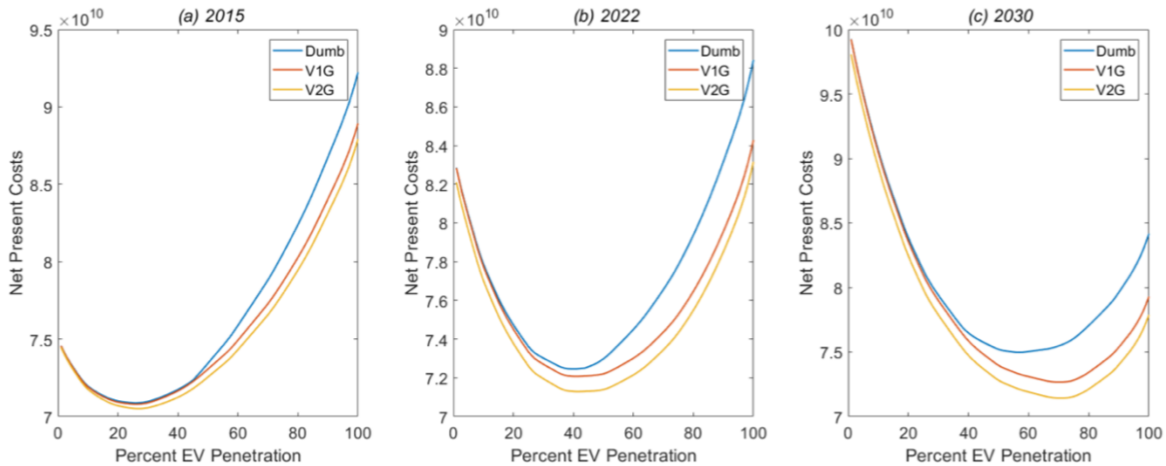

Figure 16. Total Net Present Cost for Each Percentage of EV Penetration in the Three Charging Scenarios, assuming (a) 2015 costs, (b) 2022 costs, and (c) 2030 Costs. Note that y-axis does not begin at zero.

Figure 17 shows the cost minimum EV penetration from each year from 2015 to 2030, including only (a) market costs and also (b) when including externalities. While the central results find that the optimal EV penetration in 2015 to be comparatively higher than it is now (current market share is less than 1%(IEA 2017)), there is an even sharper increase in optimal EV penetration from 2015 to 2010. Throughout the next fifteen years, there appears to be several steps where cost thresholds are reached that dramatically increase EV penetration in a short period, as EVs become cheaper than ICEVs for certain percentages of the population, including aforementioned cost premiums. Looking from 2020 to 2025, the increase in cost minimum EV penetrations is distinct between the Dumb charging scenario and the V1G and V2G charging scenario. Here communication allows for linear integration of EVs into the grid, whereas Dumb charging would cause the EV penetration to stall, especially when including externalities. The overall shape of the curves remains the about same in the two graphs, however, the thresholds of ICEV cost parity for each group of the population is reached faster, increasing EV penetrations beyond the market cost scenario. While these graphs show a high optimal deployment of EVs, such a considerable increase in EVs in Denmark as compared to their existing penetration may be difficult to reach, especially considering the recent loss of momentum (IEA 2017). However, these graphs show the societal and economic foundation to allow policymakers to sizably increase EV goals in Denmark, both in the short-term as well as the long-term future.

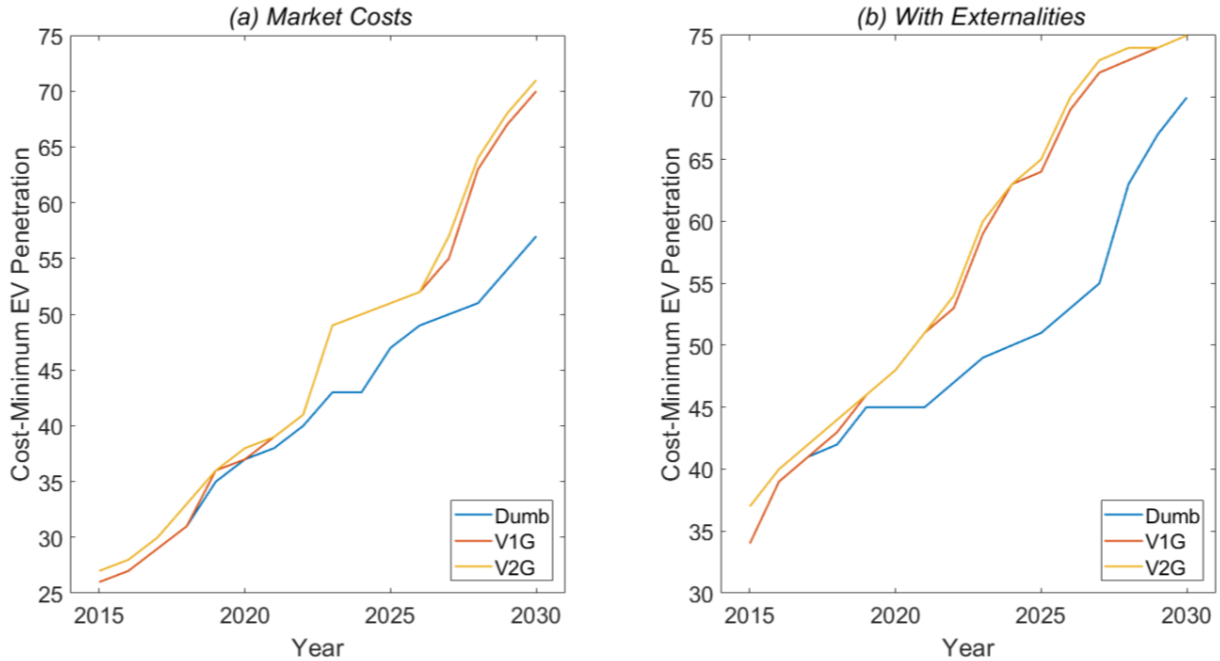

Figure 17. Minimum Cost Penetration of EVs over Time, from 2015 to 2030, for each of the Three Charging Scenarios with (a) Market Costs, and (b) Including Externalities.

Next, Figure 18 shows the amount of renewable energy used towards providing load for each EV penetration under the three communication capability scenarios, for both the years 2015 and 2030. Looking first at 2015, the graphs show the additional benefit of increased communication is especially key from "Dumb" to V1G, with the largest increase in renewable generation between these two scenarios. Both V1G and V2G increase renewable energy usage, but only to a certain point (around 20% EV penetration), where additional flexible load and storage capacity does not increase renewable energy production. However, the overall impact on renewable energy in the current grid is relatively limited, as depicted by the limited range on the y-axis. In comparison, as renewable energy capacity is expected to drastically increase by 2030, the integration of EVs and communication make a much larger impact on the amount of renewable energy used. Indeed, since renewable energy will be providing more of a baseload role, added communication is beneficial, but so is just increasing general energy demand by increasing EV penetration.

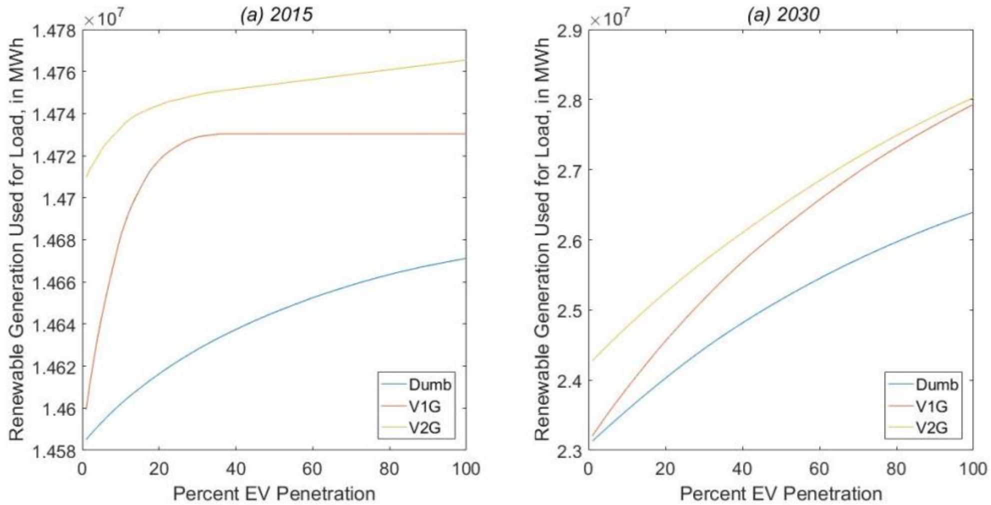

Figure 18. Renewable Generation Used for Load as EV Penetration Increases in the Three Charging Scenarios, for (a) Year 2015 and (b) Year 2030. Note that y-axis does not begin at zero.

Finally, Figure 19 shows the required construction of new natural gas as EV penetration increases for the three charging scenarios, for both the years 2015 and 2030. Most importantly, the benefit of communication ability is seen most clearly on this graph. Without any communication ability Dumb EVs, after approximately 45% penetration, would require construction of new natural gas power plants in order to meet their load. At worst case, they would require just over 3 GW assuming 100% penetration of Dumb EVs. This amount is required exclusively for new EVs, and not used for any other loads. However, when adding either V1G or V2G level of communication, the need for new natural gas capacity is entirely obviated. When looking at 2030, the overall story remains the same – without communication capabilities, Dumb EVs will require much more new natural gas capacity than either V1G or V2G-enabled EVs. However, by 2030 and over 80% EV penetration (an equivalent of 2.4 million cars), both V1G and V2G will need a minimal amount of new natural gas (<500 MW). Surprisingly, adding bidirectionality does not change the amount of requisite new natural gas capacity, as compared to V1G, implying load shifting is more important to avoided costs than energy arbitrage. The increase in requisite new capacity for 2030, as compared to the same scenarios in 2015, is due to the expected increase of the total amount of vehicles in Denmark, rather than a lack of renewable energy.

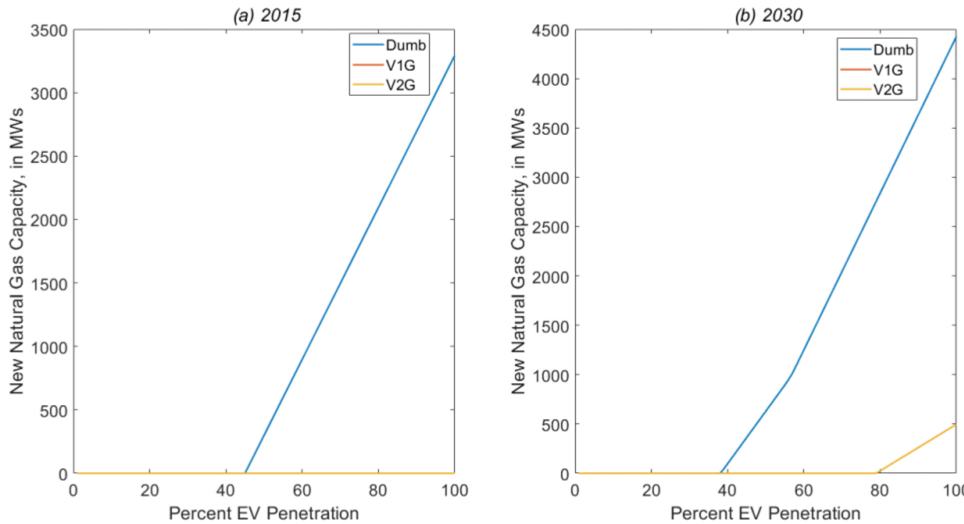

Figure 19. New Natural Gas Power Capacity Required as EV Penetration in the Three Charging Scenarios for (a) Year 2015 and (b) 2030.

4.2.4. Sensitivity Analysis

In addition to the central results that have been already presented, several sensitivity analyses were also conducted to test how the assumptions affect the results. The summary of the results of these sensitivity analyses are summarized in Table 22. First and foremost, a scenario called "Business as usual" (BAU) was calculated – this assumes characteristics similar to the current situation in Denmark, with very limited amounts of EVs (i.e., 1%). This scenario is listed first in Table 22 as a point of reference to the current costs of the Danish transportation and energy system. In addition, the central results are next presented as another point of comparison. The first sensitivity analysis conducted was to test how the assumptions of future oil costs would impact the optimal implementation of EVs, based on a projected low and high oil barrel cost cases (EIA 2017). The results are presented as a range in Table 22, and as expected, a lower future oil price greatly reduces the optimal EV penetration, while a higher future oil price greatly increases the optimal EV penetration. Thus, the evolution of future oil prices are a key factor in the optimal development of EV deployment.

Next, the following sensitivity analysis conducted tested the assumptions of how lifetime cost of the system was calculated. First, the lifespan of the cost calculations was changed down from 25 years to 12 years, to reflect the time-frame in which people own their cars (as opposed the 25-year lifespan reflecting electricity-related timeframes). Even though the discount rate remained at a social discount rate of 3%, simply reducing the time frame of the calculation has substantial impacts on the cost minimum EV penetration, reducing penetration by 18% to 27%. With or without externalities, this optimum decreases, though the cost-optimum is still an order of magnitude larger than the BAU scenario.

Analysis	Cost Minimum EV Penetration	Total System Cost (in $billion)	Total System Cost (with Externalities) (in $billion)	New Natural Gas Capacity Required (MW)
Business As Usual	1%	74.6	91.2	0
Central Results				
Market	27%	70.5	85.1	0
W/ Externalities	37%	71.0	84.8	0
Low-High Oil Cost				
Market	10%-41%	56.5-77.3	72.4-90.7	0-0
W/ Externalities	16%-56%	56.8-77.9	72.2-90.3	0-0
12 Year Lifespan				
Market	9%	46.3	55.2	0
W/ Externalities	10%	46.4	55.2	0
7% Discount Rate				
Market	9%	47.7	58.7	0
W/ Externalities	11%	47.8	58.6	0
15% Discount Rate				
Market	1%	25.0	31.6	0
W/ Externalities	1%	25.0	31.6	0
EV Tax Exempt				
Market	98%	25.3	34.5	0
W/ Externalities	99%	25.4	34.4	0
No EV Cost Premium				
Market	100%	35.8	44.844.8	00
W/ Externalities	100%	35.8		
15% Discount Rate + 2030 EV Costs				
Market	37%	15.1	20.7	0
W/ Externalities	40%	15.1	20.6	0
15% Discount Rate + EV Tax Exempt + 12 Year Lifespan				
Market	41%	10.0	14.5	0
W/ Externalities	44%	10.0	14.4	0

Table 22. Summary of Results of Various Sensitivity Analyses, all assuming V2G Communication Scenario and year 2015 (unless otherwise stated).

In a similar vein, changing the discount rate from a social discount rate to mirror a market-based discount rate of 7% likewise drastically changes the optimally deployment of EVs. Essentially the future fuel savings of EVs, when discounted to such a degree, do not pay the difference of the EV cost premiums, especially beyond the small percent who are most geared towards EV purchases (Figure 20). Thus, both market cost calculation as well as including externalities incentivize a small proportion of EVs. Because fuel savings and fuel damages in the future are discounted (even over the 25 year time frame) at such a rate, there would be much less EVs than the central results. Next, even more alarmingly, if an implied discount rate is used, based on literature that has shown individuals discounting fuel savings at 15% (Allcott & Wozny 2014; Hausman 1979), the optimal EV penetration drops to the default of 1%, even when health and climate externalities are internalized in the prices. Thus, in order to achieve socially optimal levels of EV penetration, a key barrier is to get people to think more long-term and rationally about future fuel savings and external damages – or to make calculations on the full social cost without discounting.

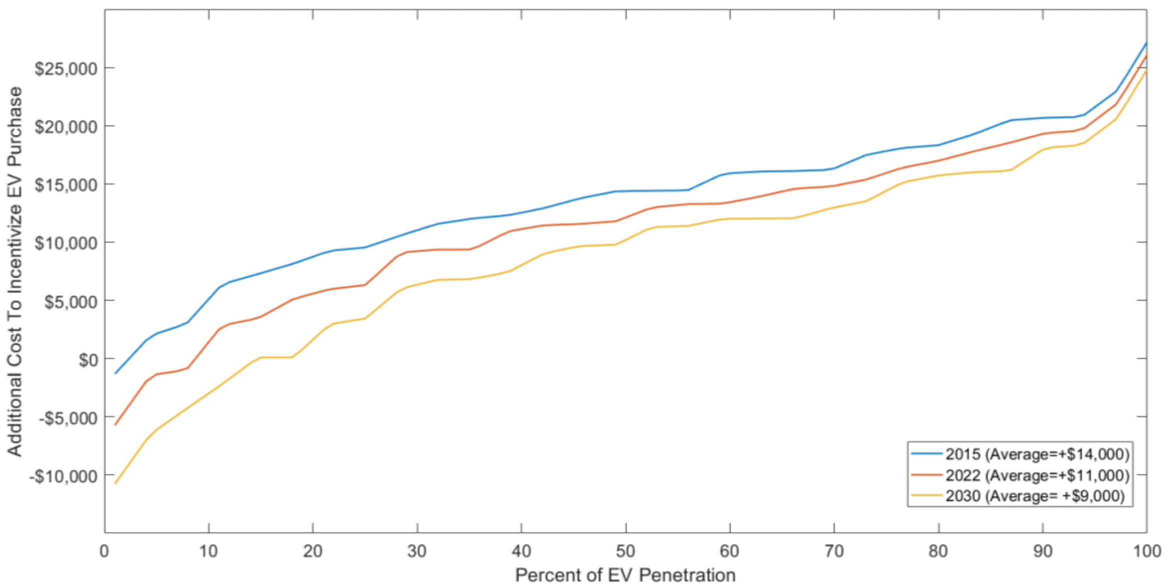

Figure 20. EV WTP Cost Premium across the Population for years 2015, 2022, and 2030 (with decreasing battery prices reducing WTP cost premium).

The next two assumptions tested regarded the comparative price of EVs, both to similar results on optimal EV penetration. First, to attempt to recreate the EV tax exemption policy Denmark had instituted in the recent past (IEA 2017), all taxes were included again on ICEVs, while keeping EVs tax exempt (but including the WTP cost premium). Whereas the EV capital cost was substantially higher and required fuel savings in order to be paid back off, the reinstatement of the EV tax exemption resulted in only slightly higher capital costs. In a similar thread, the cost premium for EVs, as based on WTP studies, was also removed, essentially assuming people have neutral preferences to purchase EVs as they have to purchase ICEVs, but excluded taxes for both EVs and ICEVs. In both of these cases these assumptions heavily tilt the results in favor of EVs, though they still have higher capital costs than the average ICEV (see Table A1) but also lower operating costs, and the analyses show the cost minimum to actually be practically 100% EV conversion. Compared to the medium amounts of EV penetration found in the central results and the previous sensitivity analyses, changing these assumptions on the capital cost of EVs is essential to the success of EV deployment.

Lastly, two more sensitivity analyses were conducted to gauge how consumers may react to EVs more realistically, i.e., using an implied individual discount rate. First, the analysis was redone using the 15% discount rate but also assuming 2030 prices of batteries, 100$/kWh (Knupfer et al. 2017). While using 15% discount rate and today's prices leads to essentially no EVs being deployed in Denmark, future battery cost reductions will cause EVs to pass capital cost thresholds such that even higher discount rates on fuel savings matter less in a consumer's choice, and results in optimal EV penetrations of around 37%. However, this substantially less than the optimal EV penetration in 2030 when including externalities, implying that waiting for the market to take care of itself would still result in suboptimal levels of EVs. Indeed, according to the model, assuming consumers are irrational about future fuel savings, EV penetration will only reach the current social optimum 15 years later (i.e. 37%).

Finally, a sensitivity analysis was conducted where the implied discount rate is used in combination with a shorter time frame, in order to capture the mindset of the average consumer faced with purchasing a vehicle, but with the reinstatement of the EV tax exemption. This combination of factors could be seen as a projection for how the average Dane would realistically react to the reinstatement of the Danish EV tax exemption. This policy, with a high discount rate over a smaller time span, would result in optimal EV penetration that are very comparable to the central results. Thus, while exempting EVs and using a more social discount rate would result in near complete conversion of the Danish transportation system, a higher implied individual discount rate would result in orders of magnitude less electrification. On the other hand, these results match very closely to what the central results presume is cost optimal, implying that the EV tax exemption would be reasonably incentivize the social optimum amount of EVs in the short-term. Nonetheless, when this analysis was conducted for the year 2030, the resulting EV penetration, 60%, was 15% lower than what the central results considers socially optimal by 2030. Thus, the EV tax exemption would be a good start to encourage optimal EV development, but the high WTP cost premium of the late majority and laggards in tandem with high discount rates require further policy mechanisms to reach the socially optimal level of EVs. In sum, electrification of personal vehicles will likely face two major barriers; the cost difference between ICEVs and EVs (especially when including WTP cost premiums), and individual tendencies to undervalue future fuel savings.

4.2.5. Conclusion & Policy Implications

The results presented in this paper show that EV penetration in Denmark is substantially less than what is socially optimal, possibly due to the actual and perceived cost differences, and the markedly inexpensive ICEVs currently. However, the model shows that optimal EV penetration to rapidly increase over the next fifteen years as both battery costs continue to drop and as renewable energy requires more controllable loads, driving down EV costs. In both cases, current EV policies should be revamped to target a rapid transition to electrification in the near- to mid-future. Along those lines, the value of the development communication and bidirectionality of EVs increases over time as EV deployment and renewable energy are both expected to grow. While the current marginal value of V1G and V2G are practically zero, it is recommended that by when EV penetration reaches about 40% (which according to model *should* be by the mid-2020's), these systems should be developed and in place for EVs, as this is when communication makes visible differences in optimal EV integration. Put another way, EVs and V2G systems achieve a social optimality, a diffusion that produces far more social and economic benefits than a transport environment wedded to fossil fuels and business as usual. The model project that a 27% penetration of V2G EVs, rising to 75% by 2030, would generate $34 billion in avoided social costs, a decrease of 30% compared to business as usual, equivalent to an annual savings of $1,200 per vehicle.

One policy implication arising from this finding is that when externalities are monetized, the social and economic benefits of a V2G transition more than pay for themselves—and the assumptions made in the model are likely conservative given that there are only projected two types of externalities, carbon and health, yet many more exist, including economic security, jobs, and enhanced competitiveness; energy security and diversification; avoided imports of oil; and other forms of pollution including water, materials, and waste. A second is that while the model calculated the amounts of costs and benefits, future research should investigate how they are distributed. Further policy analysis would be needed to confirm if the main sets of "winners" in the a V2G transition would be the drivers of cars, saving money on fuel, operations and maintenance, along with those at greater risk to the health problems associated with transport related air pollution and greenhouse gas emissions. Possible "losers" could be traditional providers of ancillary grid services, petroleum companies (selling less oil), and incumbent firms offering maintenance and servicing for ICEVs. From a technical perspective, future research should also investigate the feasibility and value of inter-day storage using V2G.

Furthermore, across both the time component of the central results as well as the sensitivity analyses, there appears to be various threshold effects that may lead EV penetration to remain low in the near term, but then exponentially balloon as cost thresholds are surpassed. With this potential growth in mind, policymakers should prepare charging infrastructure and local level grid effects not modeled here (e.g., transformer upgrades) for when a swift transition may occur. Alternatively, it may benefit society for policymakers to smooth out EV deployment in order to avoid "shocks" to the system. Keeping in mind that optimal EV penetration in 2030 is 75%, a more linear approach to EV deployment may be easier and more economically efficient to achieve. Indeed, the model shows that the socially optimal EV penetrations are orders of magnitude higher than they currently are in Denmark (IEA 2017), so policymakers may want to consider greatly increasing EV policies while concomitantly acknowledging the socially optimal level of EVs may not be feasible to achieve in the short term.

The main drivers of these thresholds are the cost differences between EVs and the tendency for individuals to use an inflated discount rate regarding future energy benefits. Thus, in tandem with preparing for a potentially rapid transition, policymakers should also act to lower these social barriers. The analysis suggests that reintroducing the tax exemption would be a good place to start, not only economically, but also signaling to the public that a transition to EVs is the future of Danish transportation may alter preferences of EVs, resulting in a reduction of WTP cost premiums, further making the transition easier and less costly. Policymakers may also consider ways to educate and inform Danish residences of the benefits of EVs to change preferences. For example, policymakers could consider implementing knowledge-based programs to advertise the better acceleration, reduction of noise, and lowering of pollution of EVs, as compared to ICEVs. Correspondingly, policymakers should also address the internal calculation of individuals purchasing vehicles, in order to correct the habitual undervaluation of fuel savings that EVs will provide. Because the central barriers of EV deployment are not technical, but rather social or economic, policymakers should consider broadening their design and scope of policy mechanisms. Despite clearing having a host of social benefits, future research should investigate the social barriers that EVs will face in Denmark, especially as the transition to large-scale EVs is underway, to ensure such advantages are secured rather than squandered.

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5. A roadmap for adoption

The final chapter of this PhD dissertation integrates, reflects and concludes on the main findings presented across the six journal articles in relation to each of the three research questions. In short, the aim is to present answers to the main overarching research enquiry: *What are the socio-technical challenges, benefits and potential of electric vehicle and vehicle-to-grid diffusion in wider society?* In addition to the three chapters above, the dissertation also presents the perspectives of other work conducted during this PhD project.

Lastly, this dissertation concludes with a potential roadmap for EV adoption and V2G based on the research introduced in this study. Aiming to not only provide avenues of diffusion within the Nordic region, this section also intends that its findings are extrapolated for international applications, both in the context of electric mobility integration as well as other technological development settings.

5.1 The electric vehicle retail space and its different consumer groups

The second chapter of this dissertation introduces two research articles in response to RQ1: *How are electric vehicles diffused in the retail and consumer level?* The first article explores the automotive retail space examining the strategies, methods and approaches of car dealerships in promoting (or failing to promote) EVs to prospective automotive consumers, resulting in the following key findings:

- Car dealerships and sales personnel serve as a major obstacle to the uptake of passenger EVs in the Nordic region, mirroring industry and government favouritism towards conventional cars, considering the lack of substantial or effective policies promoting EV diffusion.
- Policy and signalling from government and industry are evident at the point of sale, creating significant deterrents for car dealerships and sales staff to promote and intent to sell EVs.
- Evidence shows dealerships were dismissive of EVs, routinely misinformed shoppers on vehicle specifications, omitted EVs from the sales conversation and strongly oriented customers towards petrol and diesel vehicle options.
- At an individual salespersons level, the findings show that orientation towards EVs and displayed knowledge by salespersons were the most important predictors of customer EV purchase likelihood, even in markets where EV are less widely diffused such as Finland.
- Notably, the study found that non-technical barriers primarily moderated the attractiveness of EVs for dealerships to promote and sell. Considering its low profitability, lack of EV models on site, lack of personnel’s knowledge and competence about EV specifications, and

considering that EVs take longer to sell. These elements combined, result in salespersons opting to promote the easier-to-sell petrol and diesel vehicle options.

EVs challenge the structure and arrangements of the conventional automotive supply and selling chains, resulting in an unattractive product for industry and underscoring the potential systematic changes. In addition, contrary to expectations, the findings of this article challenge the image of the Nordic countries as successfully promoting innovation of low carbon-related technologies, where outside of Oslo (Norway), dealership experiences demonstrate that ordinary consumers would be highly unlikely to adopt an EV. Therefore, the main implication is that EVs are at a severe disadvantage at the retail level (the point of sale) when competing with petrol and diesel vehicle options, resulting in salespersons directing consumers away from EVs. From the retail perspective, there is little to no incentive to promote or sell EVs without more progressive action on behalf of both industry and government.

Next, the second article presented in RQ1 explored the opposite side of the retail spectrum by looking at the consumer space and the potential market for EV adoption. In summary, the study finds:

- Six specific consumer clusters around EV adoption, based on demographic and socio-economic characteristics, mobility and vehicle preferences and stated interest in EVs and V2G.
- Up to 68% of the current consumer pool is primed for EV adoption, showcasing the potential for mass market diffusion in the near term. This sample consists of three consumer groups identified as Status Seekers (technologically sensitive), Greens (environmentally sensitive) and Blue-collar Moderates (financially sensitive).
- Notably, the findings show that current EV adoption has been led by a sense of status and technology driven customers as opposed to environmentally focused.
- The capital cost (price) of electric vehicles is found to be a main determinant preventing wider adoption, where the customers that state the most interest on EVs (Greens) fall outside of the current price offerings of the EV market.
- V2G capability has the potential to increase the attractiveness of EVs to certain consumer segments, in particular to those who are interested in environmental and financial attributes, and would contribute to mass market adoption of EVs. Hence V2G will be particularly valuable for the next clusters adopting EVs, especially the Greens and Blue-collar Moderates.

In addition, the findings of this study also corroborate the results of the first article, where policy and signalling from government and industry deter purchasing of EVs, affecting both the retail (supply) and consumer (demand) space. More specifically, the second article finds that despite a large disparity between the Nordic countries in EV adoption (for example Norway has a market share of ~50% while Denmark less than 1%, see Figure 2 above) the identified consumer pool is remarkably similar across countries. That is, the current success or failure of EV adoption is a result of national policies and markets, and not due to different compositions of consumers across countries. In sum, through Chapter 2, this dissertation notes that governments and industry need to revisit transport policies and strategies to create a competitive retail and consumer space for EVs to mature, especially considering the lofty goals of large-scale decarbonization in the transport sector.

5.1.1 Other perspectives on RQ1

Beyond the work presented above, this PhD project also conducted additional research that brings relevant insights in response to RQ1. For example, when looking at the consumer space, Sovacool et. al (2018) explored the demographics of the decarbonisation of transport in greater detail, particularly passenger vehicles, noting these factors can influence preference for specific forms of mobility. Notably, consumer decisions may be irrationally influenced by antecedent and evolving dynamics of gender roles, education, conceptions of the family, age and so on, as opposed to purely economic self-interests, highlighting the value of examining the "self" in a sociotechnical system. As a result, technology adoption and trends are argued to be driven by more than purely economic rationalisation.

At the same time, Chen et. al (2018) explored the intricacies of the sociodemographic dynamics of potential automotive consumers, noting the social perception around EVs is evolving such that these technologies are becoming an absolute substitution for a petrol or diesel vehicles. That is, the authors found consumers who expressed more interest in EVs, may consider it as their main or only car in the household, replacing conventional cars (as opposed to complementing them). Consequently, this article highlights the potential for EV adoption in wider society to be the main form of passenger mobility in the near-term.

Furthering the exploration of the consumer and retail space, Noel et. al (2018) explore the consumer willingness to pay (WTP) for electric mobility, including both EV and V2G related attributes. Noting that experience with the technologies and market specific characteristics significantly affect consumer's WTP for EVs and V2G. Evidence shows that the WTP for a marginal kilometre of additional range decreases as the driving range of an EV increases; where the kilometre 151 of range (€242/km) is valued significantly higher that kilometre 401 (€91/km). The analysis also shows that WTP declines substantially after a driving range of 300-400 kms, alluding to a potential desired driving range for EVs. In other words, the race for extending the driving range of an EV may be satisfied at 300-400 kms; although this is still considerably higher than the average driving range in the Nordic region.

In terms of V2G, Noel et. al (2018) note that promoting EVs may not lead to an increase knowledge of or interest to adopt V2G, but conversely, promoting V2G may lead to an increase of EVs, as also suggested by article 2 of this dissertation. This is seconded by Chen et al (2018), noting that adding V2G capability significantly increased consumer interest in EV adoption. While, from a business perspective, industry may want to include V2G capability within EVs, since the WTP for V2G (€4,000-€5,200) was found to be substantially higher than the production costs of making an EV V2G-capable.

As such, in answering RQ1, these studies furthered the investigation of the retail and consumer space, while noting that the barriers and benefits of both EVs and V2G need to be fully explored and communicated to consumers, industry, government, and decision makers.

5.2 Weighing the barriers and benefits of electric mobility

The third chapter of this dissertation introduced two research articles answering RQ2: *What are the structural barriers and benefits of electric vehicles and vehicle-to-grid?* For this purpose, the third article presented the spectrum of barriers to EV adoption, with the following main findings:

- There was a wide variety of barriers to EVs as suggested by the experts, with a total of 53 different categories of barriers, with each expert suggesting on average 4 barriers.
- The identified barriers covered a range of topics from technical elements (range and impacts to grid), economic (price, consumer incentives), social (consumer knowledge, political will), business/industrial (OEM disinterest, business models), and environmental (winter weather).
- A nexus of barriers was identified, as experts often characterised one barrier as dependent on another one, implying that there is not just one barrier holding back EV adoption, but rather several barriers, all highly interconnected.
- The nexus consists primarily of range, price, public charging infrastructure, and mental barriers or knowledge. The 4-barrier nexus represents both the most discussed barriers and also the most interconnected barriers, where by solving a central barrier, one may also solve secondary elements.
- Barriers are highly interconnected to sociotechnical dimensions of consumer knowledge and experience, showing that social elements also moderate other commonly-perceived technical barriers, such as charging infrastructure.

While creating a portfolio of the barriers EVs face, this article finds that there are true techno-economic aspects within the identified barriers, for example, the driving range of an EV is currently lower than a comparable petrol or diesel vehicle, or the retail price tends to be higher in comparable models. However, these barriers are found to be linked to social aspects such as knowledge and experience and notably, responding to social elements which may prove to be more effective and less-costly policy strategies in alleviating the current challenges of EVs. The clear example is charging infrastructure, where there is a debate between furthering a charging network of rapid chargers or developing consumer knowledge and awareness campaigns in residential areas to encourage home charging. This may point towards harmonised policy solutions that account for both the technical and non-technical aspects of the system.

To complement the barriers of EV adoption, the dissertation next moved onto looking at the plethora of benefits offered by EVs and V2G. This is introduced with the fourth article of this dissertation, which concluded:

- 29 different categories of EV benefits were identified, with the five most commonly discussed being: low emissions, noise reduction, better performance, economic savings, and renewable energy integration.
- 25 different categories of V2G benefits were identified with the top four being: renewable energy integration, controlled charging, vehicle-to-home and transmission system operator (TSO) services. However, the benefits of V2G were much more pluralistic compared to the experts' view of EV benefits, as the overall knowledge of V2G was less defined.
- V2G is primarily associated with residential solar PV and vehicle-to-home, as opposed to the system-wide uses, e.g. TSO grid services.
- The interconnection and colliding effects of novel benefits should be further explored, such as noise reduction that in turn support the reconceptualization of urban design and planning.

Notably while a plethora of benefits for both EV and V2G are identified, many of these benefits had remained underexplored both in the literature as well as in tangible applications of the technology in society. Therefore, there is a need to focus more on communicating these benefits, by creating visibility and awareness across consumers, industry and decision-makers. As seen in Chapter 2, consumer knowledge can act as a powerful element in fostering social wide adoption of EVs and V2G. Ultimately, Chapter 3 of this dissertation exhibits both the plethora of barriers faced and benefits to be captured in the diffusion of electric mobility, setting a foundation to which these identified elements can and should be socially communicated and potentially addressed.

5.2.1 Other perspectives on RQ2

Other research was conducted during this PhD project that also brings insight to RQ2. For example, Noel et al (2019) explores in particular two interconnected EV barriers, charging infrastructure and consumer knowledge, by examining the roots of range anxiety. The central finding was that driving range concerns continue to be a primary reason for consumer disinterest on EVs, in spite of the technological advances in batteries and further development of charging networks. Also recognizing the interconnectedness of EV barriers (as proposed by the third article of this dissertation), Noel et al (2019) find collateral barriers such as charger anxiety, where chargers are oversaturated (too many EV drivers on the road) and will not be available for consumer to charge. Thus this paper furthers a notion of the evolution in the rhetoric of EV barriers such as moving from range anxiety to charger anxiety. Notably, a conclusion is that it may be more relevant to focus on the knowledge aspects of EV barriers, as opposed to a comprehensive, but expensive charging infrastructure policy. That is, the focus in an extensive charging network may not lead to further EV adoption, as the paper elaborates through the cases of Estonia or Better Place in Denmark (both of which developed comprehensive charging networks that resulted in nearly no increase in EV adoption).

Furthermore, Noel et al (2018a) adds to the notion that the benefits and attributes of EV and V2G need to be further and more explicitly communicated to consumers, industry and decision makers in order to foster EV adoption. Specifically, the authors found that marketing strategies should highlight the technological and status attributes of electric vehicles more to consumers, as opposed to other elements, such as environmental aspects. The finding notes that EV adoption is led by the conspicuousness, where consumers are attracted to luxury and unique attributes of EVs, implying there should be stronger focus on status in EV diffusion. Using the case of Tesla and Nissan Leaf as evidence, this article also furthers the finding of research article two of this dissertation.

More generally, Sovacool et al (2018a) and Sovacool et al (2018b) explore the challenges to the transport and electricity sectors in the Nordic countries. Notably, many of these attributes relate to both the challenge of EV integration as well as the potential value of doing so. On the electricity side, the main challenges are the integration of renewables, electrification of transport and other sectors, managing intermittency, carbon intensity and climate change, supporting local grids, and ensuring adequate capacity. Through electrifying passenger transportation and the use of V2G, EVs can, at least to some extent, alleviate these challenges by providing additional power load to balance the grid, provide services to mitigate intermittency, and foster renewable energy integration. As such, the following section of this dissertation discusses the findings from the system level analysis of Chapter 4.

5.3 A systemic impact of electric mobility

The fourth chapter of this dissertation introduced two research articles in response RQ3: *What is the system impact of electric vehicles and vehicle-to-grid?* In doing so, the fifth article presented the current and future business implications of EVs, addressing the system effects of EV diffusion from a business and supply chain perspective, with the main findings:

- EVs currently face an unfavourable business case, due to the legacy of the internal combustion car industries, along with the national market conditions favouring the existing regime.
- As a result, EVs currently have an unsuitable business model which compromises the production and promotion, resulting in in less profitable product lines for industry and unaffordable vehicles for consumers.
- For the industry, the development of EVs conflicts with the nested investments on their ICEV product lines, requiring substantial changes to their selling methods (i.e. dealerships), component manufacturers, maintenance networks and refuelling (recharging) networks. In short, all these elements create deterrents across the system to promote and sell EVs.
- For a system-wide diffusion, EVs will require a transformation in the traditional automotive selling chain, directly affecting selling methods, maintenance revenue streams and refuelling (recharging) structures and related business models.
- Hence there is a need to adopt a new system to minimise the obstacles in transitioning to EVs, and to maximise the benefits of such a transition. This article thus introduces to this dissertation the system effects of EV diffusion from a business and supply chain perspective.

This article concludes there are four thematic areas of impact at a system level: unfavourable business cases, reduction or elimination of maintenance business units, challenging supply and manufacturing capacity to meet desired EV volumes, and the need of charging infrastructure. Therefore, the system implications are clear, diffusion of EVs conflicts with the nested legacy (and investments) of the petrol and diesel car industries, creating two main elements of disruption. The first is that current EV production and promotion is not tailored for EVs. Instead industry uses existing internal combustion engine structures, which results in an unprofitable product for industry to sell and consumer to buy; as also presented in Chapter 2 with the micro-level perspective in the retail and consumer space. The second element is that EVs face a different type of returns on investment as compared to the internal combustion engine industry, affecting traditional revenue streams, e.g., disrupting maintenance supply networks. Consequently, new business structures need to be created to better fit EVs and optimise their production and market delivery, while fitting within, or at least not entirely disrupting automotive industry's structure and method of selling cars. This means applying existing relevant skills and processes to sell new types of cars (EVs), as opposed continuing the process of petrol and diesel vehicle sales.

The sixth article of this dissertation, also answering RQ3, investigated the social costs and benefits of different system configurations of EVs, including and excluding the use of V2G. The article concludes that:

- The most cost-effective penetration of EVs in the immediate future is 27%, increasing to 75% by 2030, which would account to a reduction of $34 billion in societal costs in 2030, a decrease of 30% compared to a business-as-usual scenario.

- Different levels of penetration of EV communication ability reduce the use of conventional generation and increase the utilisation of renewable generation. V1G smart charging decreases spilled renewable generation by 21%, and V2G storage decreases spilled renewable generation by 45% over the modelled year.

- Increased communication ability in EV penetration reduces significantly the need of new additional conventional power generation built into the electricity system. Specifically, when adding either V1G or V2G levels of communication, the need for new natural gas capacity is entirely obviated; whereas any communication, a fleet comprised entirely of Dumb EVs would require construction of new natural gas power plants in order to meet their load needed ~3 GW of new gas plans.

- However, today's unfavourable market conditions for EVs, such as capital cost differences or lack of willingness to pay, coupled with consumer discount rates, represent substantial barriers for EV penetration in Denmark.

The implications of the sixth article are clear, EVs and V2G have the potential to significantly reduce social costs in the short, medium and long term. Notably, these electric-powered technologies would also create positive spill over effects by integrating renewable energy and better utilising resources, mitigating the need for new conventional power generation. Moreover, this does not include the potential of inter-day energy arbitrage of V2G and how driving demands would implicate long-term V2G storage. However, while the system impacts appear overall to be positive, a key finding is that above 80% of EV penetration, WTP cost premiums for EVs becomes prohibitively expensive, inhibiting adoption. Consequently, the later stages of the electrification of transport will likely face consumer resistance to EV adoption (as also seen in Chapter 2's consumer groups analysis with groups such as Petrol Heads or Sceptics). In addition, this may prove to be a challenge for governments and industry, if the wish is to completely phase-out the selling (and purchasing) of petrol and diesel cars in the near future.

In summary, Chapter 3 of this dissertation shows the system impacts of EVs and V2G, both from a business and supply chain perspective, as well as from a power grid and societal perspective. While there are structural challenges to be addressed by tailoring the supply and selling chain to EVs, the benefits appear to be clear, with significant societal value to be captured, along with meeting decarbonisation targets.

5.3.1 Other perspectives on RQ3

In looking at other perspectives to answer RQ3, this dissertation can first look at Sovacool et. al (2018c) investigation of the impact of V2G on business and industry, by identifying twelve meaningful stakeholder types and corresponding business markets. The authors noted that a V2G transition would maximise the benefits of EVs by improving the efficiency and profitability of electricity grids, reduce greenhouse gas emissions, integrate renewable energy, and capture cost savings for owners, drivers, and other users. Importantly, Sovacool et. al (2018c) note that V2G may substantially challenge the conventional structures, not only on the petrol and diesel car industries but also the conventional business models and systems of the electricity sector through a decentralised, dynamic and circular system. In short, V2G can act as an empowerment of power flows creating value across the electricity sector. The system impacts, though, are identified as having elements of temporality as the technology matures and diffuses across society.

Furthermore, when looking at the system effects of electric mobility, Sovacool et al (2019) explores the justice effects of an EV and V2G diffusion across distributive, procedural, cosmopolitan and recognition justice. For example, such justice impacts include that EVs are luxury goods only benefiting the consumers with means of access, or that a social wide EV diffusion could contribute to externalities from the large-scale production of batteries or production of particle matter from tires friction, and even the potential loss of jobs on the traditional petrol and diesel industries. Hence, some of these elements may also be presented as barriers for diffusion. As seen in Chapter 2 and Chapter 3, such justice issues may exacerbate the loss of revenue at a car dealership level or loss of jobs from lack of technology knowledge from sales personnel. In spite of this, as seen in Chapter 4, the modelled value of EV and V2G diffusion shows potential savings in societal costs of up to 30% by 2030 with the additional value of renewable energy integration and grid balancing capabilities. The implication is that while there is inherent value to be captured from an EV diffusion, we must also consider the points of system stress where EVs and V2G may affect the existing elements of the system.

Finally, Zarazua de Rubens et al. (2018) explore the system impacts in super electricity grids, where EVs and V2G may contribute in the integration not only of renewable energy technologies but also in other relevant infrastructures, namely supergrids. This in turn would allow for greater value-capturing opportunities considering that, through the supergrid, multiple countries would benefit from cross sector decarbonisation. Hence the electric mobility integration in the Nordic countries could also benefit other parts of Europe, in actual system effects by contributing to the balancing of other European grids by allowing additional renewable energy capacity on their grids.

5.4 A road for electric mobility adoption

The final section of the dissertation concludes with a prospective roadmap for electric mobility adoption, utilising the research outputs introduced to answer the three research questions, proposing specific measures to create a space in which EVs can be produced, promoted, operated, and diffused into wider society. As discussed above, EVs are recognised as the main technology to decarbonise passenger transportation, and when coupled with a low-carbon electricity system, society can capture a plethora of co-benefits. These include renewable energy integration, grid-balancing services, on-site power supply for a local load provider, reduction in noise, among others; all of which would result in value-capturing processes and ultimately social cost savings, ultimately enabling and maximising its decarbonisation potential. The recommendations of this roadmap are organised within the socio-technical e-mobility landscape across three levels: consumers level, industry, and government and decision makers.

5.4.1 Reaching consumer markets

From the results of this dissertation, recommendations arise regarding price, range, promotion theme and inclusion of V2G.

The maximum price of EVs should be considered to be around €30,000 in order reach a mass market. As presented in this dissertation, between 84%-94% of respondents within each consumer group expects to consider a vehicle of <=€30,000. In some regards, this tipping point will be overcome in time as the technology matures and economies of scale develop. However, in the short and medium term, or at least until EVs reach this price range, governments should create incentives to position EV competitively in the market (see 5.4.3 below). A reduction in cost as forecasted would position EVs within the stated price range of the consumer groups most interested on the technology and would allow access to mass market consumer pools.

Regarding the range of EVs, this dissertation both presents that up to 90% of respondents state to drive <50kms/day, and up to 97% of the survey sample states to drive less than 80kms/day. Even in harsh conditions, EVs would still meet the daily driving requirements of the majority of people, without needing to charge. Moreover, range beyond 300 km is not as urgent, as shown by the WTP premium as driving range decreases sharply after a range of 300-400km. Hence EV OEMs should consider this as the potential sufficient threshold in the quest for further driving range. Once EV options can offer this range, additional km might not result in an optimal product offering.

Next, the promotion and messaging strategy of EVs should focus primarily on the technological and status-related attributes, as opposed to solely on the environmental attributes. When advertising an EV (which itself should be done more often), the strategy should focus on targeting specific consumer segments in a layered approach. For example, considering that current EV adoption is led by a sense of status, short-term EV promotion should appeal to the technological, status and luxury aspects of EVs (e.g. faster acceleration, more comfortable driving, less noise). However, as price is reduced and EVs can be positioned below the €30,000 threshold discussed above, the strategy should shift to target other consumer segments, and highlight more actively the environmental or cost-saving attributes of EVs.

Lastly, V2G capability has the potential to increase the attractiveness of EVs to consumers, particularly those interested in environmental and financial attributes, which would comprise the mainstream consumers. Hence, automotive manufacturers should consider including V2G capability in their commercially available EVs in order to reach the mainstream. Indeed, it is a cost-effective approach to increase the attractiveness to the mainstream consumer, considering that the WTP for V2G is significantly higher than the potential cost of developing V2G capability in EVs.

5.4.2 Industry and business sector

This dissertation provides recommendations for industry across two levels. The first being the retail space through car dealerships, and the second at an industry and supply chain level.

First, dealers should provide training schemes for all staff, including executives and sales personnel to improve the knowledge, confidence and willingness to engage with EV technology, and in turn promote it and sell it. These training schemes could focus on EV technology, vehicle specifications, and revised sales processes. The intention is also to further operationalise the sale process to reduce lead times, as it has been shown EVs can take 2-4 times more time to sell as compared with petrol or diesel option, due to the additional knowledge dissemination processes with the customer. This recommendation would address the findings of Chapter 2, which found that lack of dealer knowledge, longer sales time of EVs, and less profitable to sell were barriers that discourage salespersons to engage with EV technology.

The second recommendation focuses on sales commissions, bonuses and incentives around EV technology. This dissertation encourages industry to revise the reward schemes for sales personnel to further encourage engagement with the technology. Considering that currently EVs are not only a more difficult and slower product to sell, affecting the ratio of sales and thus the commissions earned, but also, commissions tend to be lower in comparison to petrol or diesel option, since EVs are generally less profitable. While this will in part be addressed over time as EVs mature and economies of scale create a more lucrative product, in the short-term industry should look for avenues to incentivise the active promotion of EV at the sales floor in car dealerships. Notably, industry may face little to no incentive to switch these strategies since petrol and diesel car sales are more profitable and thus, it might require government intervention to initiate these types of strategies.

Moreover, it is recommended for industry to increase the visibility of EV promotion across different outlets, especially focusing on the status and technological aspects of EVs in the short term, and subsequently on the environmental and cost-saving attributes as the EV reaches later customer segments. For example, at a dealership level, EV products and information on specification must be visible to consumers, communicating the availability EV models and brands within dealerships. In addition, promotional material should extend beyond the sales floors through marketing strategies such as demo vehicles, trial events, and promotional material. The aim is to fully communicate the benefits and specification of EV technology to foster consumer knowledge and awareness. In doing so, industry would look to position EVs on an equal footing within the sales conversations and individual consumer negotiation when comparing to other vehicle alternatives.

Finally, industry should look to develop tailored business models, supply chain and selling processes for EVs that look to optimise the production and delivery of models into the retail market. As described in Chapter 2 and Chapter 3, EV production and delivery have utilised the existing structure of petrol and diesel vehicles, compromising the value proposition of an EV, and thus creating an unprofitable product to sell and for consumers to buy. At its core, the recommendation is to develop dedicated supply chain lines for EVs. Beyond assembly lines, business models should be fitted for EV technology, for example, revising the traditional dealership model, in the way Tesla has done it via showrooms, or even following purchasing trends and completely eliminating dealerships (as described in Chapter 3 above). Notably, in the short term, these business models for EVs must fit within, or at least not entirely disrupt, automotive industry's structure and method of selling cars.

5.4.3 Government and decision makers

For government, the implication is, at its core, straight forward: creating a competitive space for EVs to compete within the automotive market, if these vehicle technologies are to be used as the main tool to decarbonise passenger transportation.

The first recommendation is that government should work towards developing a policy mix that allows EVs to be more competitively priced in the retail market, coinciding with the demands from a consumer perspective. As noted above, governments should consider a price of an EV at €30,000 or less, until battery prices decrease and the technology matures enough where it can EVs can be offered within a €20,00-€30,000 price range. Considering that the price is shown as a primary challenge in Chapter 2 where EV prices discourage dealers to include EV within sales conversation (first article), position EV outside of the potential mainstream market (second article); in Chapter 3 industry experts noting price as the main EV barrier (third article); and Chapter 4, noting current EV price as the main challenge so reaching the social optimal penetration of EVs (sixth article).

Thus, it may be wise for governments to allocate available funds to first address the barrier of price, before moving onto dealing with charging infrastructure and range anxiety.

In terms of EV charging, the recommendation is for governments to be wary of dedicating a large portion of available funds to develop charging networks. Instead, a less costly and more efficient method to remove barriers around EV charging would be to address consumer knowledge, at least in the short to medium term. Moreover, if government were to incentivise charging infrastructure, it may be wise for government to prioritise home and work-based charging as opposed to public charging, especially as the latter has yet to show effective revenue models from lack of demand and as most charging demand can be met at home and work places. On the other hand, public charging networks are important to create visibility and awareness of EV technology.

Importantly, considering both the need to incentivise EVs to foster diffusion for decarbonisation purposes, while also reducing the use and fossil fuel-based vehicle technologies, governments need to revise the entire spectrum of transport policies in order to create a harmonised policy portfolio where incentives and actions are coordinated across technologies. In doing so, policymakers should seek a portfolio of social and economic carrots to increase EV diffusion while also including a set of sticks to disincentive carbon-intensive behaviour. An example would be the bonus-malus system discussed in Chapter 2 where EV incentives are harmonised with fossil-fuel disincentives. This would alleviate one of the main overarching findings of this dissertation, where EVs are currently at a disadvantage across different levels of the automotive sector, where the net effect of current policy mixes has not created an equal space for EVs to compete. Hence policy must be harmonised to create an equal playing field for EV diffusion.

In terms of V2G, there are two levels of recommendations for governments. First from a transportation standpoint, V2G is found to be an attractive element to the potential mainstream market of EVs, therefore governments should consider to require V2G capabilities within EVs, to create a more attractive technology and ease transportation decarbonisation goals. This could be done via grants for V2G research or installation of V2G capable charging stations and even grants to address potential capital costs of the technology such as consumer grants for purchasing an V2G-capable EV. Admittedly, this would coincide with industry goals, as V2G would potentially make EVs more attractive for consumers, considering that the WTP for V2G is found to be significantly higher than the potential cost of production. The second element is that, as seen in Chapter 4 (article six), enabling communication ability of EVs captures additional social and system benefits, such as renewable energy integration and thus reducing the need of new fossil-based power production. Therefore, incentivising V2G would not only mean less difficult diffusion of EV technology and the decarbonisation of transport, but also would contribute to the decarbonisation of the electricity sector. Ultimately government intervention is necessary to maximise the value of electric mobility.

In sum, this PhD project explores the diffusion of EVs and V2G across three thematic elements, each representing a level of analysis on this dissertation: consumer and retail level, meso-level, and system wide implications. In doing so, it provides an understanding on how EVs and V2G are currently and will continue to penetrate society, following a socio-technical preconception of the electric mobility space and how this technology interacts across systems in society. Ultimately, this PhD dissertation provides a roadmap for EV and V2G adoption, within the Nordic region but also internationally, which can in turn serve as a map for technology innovation and diffusion in general.

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6.2 Co-author statements for PhD dissertation

The statements are presented in the same order as introduced on the dissertation: article 1-6 (note article 2 is single author and it is not reported on this appendix).

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Declaration of co-authorship*

Full name of the PhD student: Gerardo Zarazua de Rubens

This declaration concerns the following article/manuscript:

Title:	Dismissive and deceptive car dealerships create barriers to electric vehicle adoption at the point of sale
Authors:	G. Zarazua de Rubens, L. Noel, and B.K. Sovacool

The article/manuscript is: Published [X] Accepted [ ] Submitted [ ] In preparation [ ]

If published, state full reference:

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If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No [X] 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	B
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
	Lance Noel	[signature]
	Benjamin K. Sovacool	[signature]

In case of further co-authors please attach appendix

Date: 07 December 2018

*As per policy the co-author statement will be published with the dissertation.

SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship*

Full name of the PhD student: Gerardo Zarazua de Rubens

This declaration concerns the following article/manuscript:

Title:	Understanding the Socio-technical Nexus of Electric Vehicle (EV) Barriers: A qualitative discussion of Range, Price, Charging and Knowledge.
Authors:	L. Noel, G. Zarazua de Rubens, J. Kester and B.K. Sovacool

The article/manuscript is: Published ☐ Accepted ☐ Submitted ☒ In preparation ☐

If published, state full reference:

If accepted or submitted, state journal:

Energy Policy

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:

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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	B
6. Finalization of the manuscript and submission	C

Signatures of the co-authors

Date	Name	Signature
	Lance Noel	
	Benjamin K. Sovacool	
	Johannes Kester	

In case of further co-authors please attach appendix

Date: 07 December 2018

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AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship*

Full name of the PhD student: Gerardo Zarazua de Rubens

This declaration concerns the following article/manuscript:

Title:	'Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)
Authors:	L. Noel., G. Zarazua de Rubens, J. Kester and B.K. Sovacool

The article/manuscript is: Published [X] Accepted [ ] Submitted [ ] In preparation [ ]

If published, state full reference:

Noel, L, Zarazua de Rubens, G, Kester, J & Sovacool, B 2018, 'Beyond emissions and economics: Rethinking the co-benefits of electric vehicles (EVs) and vehicle-to-grid (V2G)' Transport Policy, vol. 71, pp. 130-137.

If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No [X] 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	B
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	C

Signatures of the co-authors

Date	Name	Signature
	Lance Noel	
	Benjamin K. Sovacool	
	Johannes Kester	

In case of further co-authors please attach appendix

Date: 07 December 2018

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AARHUS UNIVERSITY

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship*

Full name of the PhD student: Gerardo Zarazua de Rubens

This declaration concerns the following article/manuscript:

Title:	The market case for electric mobility: Investigating electric vehicle business models for mass adoption
Authors:	G. Zarazua de Rubens, L. Noel , J. Kester and B.K. Sovacool

The article/manuscript is: Published ☐ Accepted ☐ Submitted ☒ In preparation ☐

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If accepted or submitted, state journal:

Energy Policy

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

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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

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1. Formulation/identification of the scientific problem	B
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	A

Signatures of the co-authors

Date	Name	Signature
	Lance Noel	
	Benjamin K. Sovacool	
	Johannes Kester	

In case of further co-authors please attach appendix

Date: 07 December 2018

*As per policy the co-author statement will be published with the dissertation.

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AARHUS UNIVERSITY

Declaration of co-authorship*

Full name of the PhD student: Gerardo Zarazua de Rubens

This declaration concerns the following article/manuscript:

Title:	Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark
Authors:	L. Noel, G. Zarazua de Rubens, and B.K. Sovacool

The article/manuscript is: Published [X] Accepted [ ] Submitted [ ] In preparation [ ]

If published, state full reference:

Noel, L, Zarazua de Rubens, G & Sovacool, B 2018, 'Optimizing innovation, carbon and health in transport: Assessing socially optimal electric mobility and vehicle-to-grid pathways in Denmark' Energy, vol. 153, pp. 628-637. https://doi.org/10.1016/j.energy.2018.04.076

If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

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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	C

Signatures of the co-authors

Date	Name	Signature
	Lance Noel	
	Benjamin K. Sovacool	

In case of further co-authors please attach appendix

Date: 07 December 2018

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6.3 Overview of interviews by respondent number

Respondent Number	Country	Location	Date
R1	Iceland	Reykjavik	September, 2016
R2	Iceland	Reykjavik	
R3	Iceland	Reykjavik	
R4	Iceland	Reykjavik	
R5	Iceland	Reykjavik	
R6	Iceland	Reykjavik	
R7	Iceland	Reykjavik	
R8	Iceland	Reykjavik	
R9	Iceland	Reykjavik	
R10	Iceland	Reykjavik	
R11	Iceland	Reykjavik	
R12	Iceland	Reykjavik	
R13	Iceland	Reykjavik	
R14	Iceland	Reykjavik	
R15	Iceland	Reykjavik	
R16	Iceland	Reykjavik	
R17	Iceland	Reykjavik	October 2016
R18	Iceland	Reykjavik	
R19	Iceland	Reykjavik	
R20	Iceland	Reykjavik	
R21	Iceland	Reykjavik	
R22	Iceland	Reykjavik	
R23	Iceland	Reykjavik	
R24	Iceland	Reykjavik	
R25	Iceland	Reykjavik	
R26	Iceland	Reykjavik	
R27	Iceland	Reykjavik	
R28	Iceland	Reykjavik	
R29	Iceland	Akureyri	
R30	Iceland	Akureyri	
R31	Iceland	Akureyri	
R32	Iceland	Akureyri	
R33	Iceland	Akureyri	
R34	Iceland	Akureyri	
R35	Iceland	Akureyri	
R36	Iceland	Reykjavik	
R30	Sweden	Stockholm	November 2016
R31	Sweden	Stockholm	
R32	Sweden	Stockholm	

R33	Sweden	Stockholm	
R34	Sweden	Stockholm	
R35	Sweden	Stockholm	
R36	Sweden	Stockholm	
R37	Sweden	Stockholm	
R38	Sweden	Stockholm	
R39	Sweden	Stockholm	
R40	Sweden	Stockholm	
R41	Sweden	Stockholm	
R42	Sweden	Stockholm	
R43	Sweden	Stockholm	
R44	Sweden	Stockholm	
R45	Sweden	Stockholm	
R46	Sweden	Stockholm	
R47	Sweden	Stockholm	
R48	Sweden	Stockholm	
R49	Sweden	Stockholm	
R50	Sweden	Stockholm	
R51	Sweden	Stockholm	
R52	Sweden	Stockholm	
R53	Sweden	Gothenburg	
R54	Sweden	Gothenburg	
R55	Sweden	Gothenburg	
R56	Sweden	Gothenburg	
R57	Sweden	Gothenburg	
R58	Sweden	Gothenburg	
R59	Sweden	Gothenburg	
R60	Sweden	Gothenburg	
R61	Sweden	Gothenburg	
R62	Sweden	Gothenburg	
R63	Sweden	Gothenburg	
R64	Sweden	Gothenburg	
R65	Sweden	Gothenburg	
R66	Sweden	Gothenburg	
R67	Sweden	Gothenburg	
R68	Sweden	Gothenburg	
R69	Sweden	Gothenburg	
R70	Sweden	Lund/Malmo	
R71	Sweden	Lund/Malmo	
R72	Sweden	Lund/Malmo	
R73	Sweden	Lund/Malmo	
R74	Sweden	Lund/Malmo	
R75	Sweden	Stockholm	

R76	Sweden	Stockholm	
R77	Sweden	Stockholm	December 2016
R78	Sweden	Lund/Malmo	
R79	Denmark	Other	January 2017
R80	Denmark	Copenhagen	
R81	Denmark	Copenhagen	February 2017
R82	Denmark	Copenhagen	
R83	Denmark	Copenhagen	
R84	Denmark	Copenhagen	
R85	Denmark	Copenhagen	
R86	Denmark	Copenhagen	
R87	Denmark	Copenhagen	
R88	Denmark	Copenhagen	
R89	Denmark	Copenhagen	
R90	Denmark	Copenhagen	
R91	Denmark	Copenhagen	
R92	Denmark	Copenhagen	
R93	Denmark	Copenhagen	
R94	Denmark	Copenhagen	
R95	Denmark	Copenhagen	
R96	Denmark	Copenhagen	
R97	Denmark	Copenhagen	
R98	Denmark	Copenhagen	
R99	Denmark	Copenhagen	
R100	Denmark	Copenhagen	
R101	Denmark	Copenhagen	
R102	Denmark	Copenhagen	
R103	Denmark	Copenhagen	
R104	Denmark	Copenhagen	
R105	Denmark	Copenhagen	
R106	Denmark	Copenhagen	
R107	Denmark	Copenhagen	
R108	Denmark	Copenhagen	
R109	Denmark	Copenhagen	
R110	Denmark	Copenhagen	
R111	Denmark	Copenhagen	
R112	Denmark	Copenhagen	
R113	Denmark	Copenhagen	
R114	Denmark	Copenhagen	
R115	Denmark	Copenhagen	
R116	Denmark	Aarhus	
R117	Denmark	Aarhus	
R118	Denmark	Other	

R119	Denmark	Aarhus	
R120	Denmark	Aarhus	
R121	Denmark	Aarhus	
R122	Denmark	Aarhus	
R123	Denmark	Aalborg	
R124	Denmark	Aalborg	
R125	Denmark	Aalborg	
R126	Denmark	Aalborg	
R127	Denmark	Aalborg	
R128	Denmark	Aalborg	
R129	Denmark	Copenhagen	March 2017
R130	Denmark	Aalborg	
R131	Denmark	Copenhagen	
R132	Denmark	Aalborg	
R133	Denmark	Aalborg	
R134	Finland	Helsinki	
R135	Finland	Helsinki	
R136	Finland	Helsinki	
R137	Finland	Helsinki	
R138	Finland	Helsinki	
R139	Finland	Helsinki	
R140	Finland	Helsinki	
R141	Finland	Helsinki	
R142	Finland	Helsinki	
R143	Finland	Helsinki	
R144	Finland	Helsinki	
R145	Finland	Helsinki	
R146	Finland	Helsinki	
R147	Finland	Helsinki	
R148	Finland	Helsinki	
R149	Finland	Helsinki	
R150	Finland	Helsinki	
R151	Finland	Helsinki	
R152	Finland	Helsinki	
R153	Finland	Helsinki	
R154	Finland	Helsinki	
R155	Finland	Helsinki	
R156	Finland	Helsinki	
R157	Finland	Helsinki	
R158	Finland	Helsinki	
R159	Finland	Helsinki	
R160	Finland	Helsinki	
R161	Finland	Helsinki	

R162	Finland	Helsinki	
R163	Finland	Helsinki	
R164	Finland	Helsinki	
R165	Finland	Helsinki	
R166	Finland	Helsinki	
R167	Finland	Helsinki	
R168	Finland	Tampere	
R169	Finland	Tampere	
R170	Finland	Tampere	
R171	Finland	Tampere	
R172	Finland	Tampere	
R173	Finland	Tampere	
R174	Finland	Tampere	
R175	Finland	Tampere	
R176	Finland	Tampere	
R177	Finland	Tampere	
R178	Finland	Helsinki	
R179	Finland	Oulu	
R180	Finland	Oulu	
R181	Finland	Oulu	
R182	Finland	Oulu	
R183	Finland	Oulu	
R184	Finland	Oulu	
R185	Finland	Oulu	
R186	Finland	Oulu	
R187	Finland	Helsinki	
R188	Finland	Tampere	
R189	Finland	Oulu	
R190	Finland	Oulu	
191	Norway	Oslo	April 2017
R192	Norway	Oslo	
R193	Norway	Oslo	
R194	Norway	Oslo	
R195	Norway	Oslo	
R196	Norway	Oslo	
R197	Norway	Oslo	
R198	Norway	Oslo	
R199	Norway	Oslo	
R200	Norway	Oslo	
R201	Norway	Oslo	
R202	Norway	Oslo	
R203	Norway	Oslo	
R204	Norway	Oslo	

R205	Norway	Oslo	
R206	Norway	Oslo	
R207	Norway	Oslo	
R208	Norway	Oslo	
R209	Norway	Oslo	
R210	Norway	Oslo	
R211	Norway	Oslo	
R212	Norway	Oslo	
R213	Norway	Oslo	
R214	Norway	Oslo	
R215	Norway	Oslo	
R216	Norway	Oslo	
R217	Norway	Oslo	
R218	Norway	Oslo	
R219	Norway	Oslo	
R220	Norway	Oslo	
R221	Norway	Oslo	
R222	Norway	Oslo	
R223	Norway	Oslo	
R224	Norway	Oslo	
R225	Norway	Oslo	
R226	Norway	Oslo	
R227	Norway	Oslo	
R212	Norway	Oslo	
R213	Norway	Oslo	
R214	Norway	Oslo	
R215	Norway	Oslo	
R216	Norway	Oslo	
R217	Norway	Oslo	
R218	Norway	Oslo	
R219	Norway	Oslo	
R220	Norway	Oslo	
R221	Norway	Oslo	
R222	Norway	Oslo	
R223	Norway	Oslo	
R224	Norway	Oslo	
R225	Norway	Oslo	
R226	Norway	Oslo	
R227	Norway	Oslo	
R228	Norway	Oslo	
R229	Norway	Oslo	
R230	Norway	Oslo	
R231	Norway	Oslo	

R232	Norway	Oslo	
R233	Norway	Oslo	
R234	Norway	Oslo	
R235	Norway	Oslo	
R236	Norway	Trondheim	May 2017
R237	Norway	Trondheim	
R238	Norway	Trondheim	
R239	Norway	Trondheim	
R240	Norway	Trondheim	
R241	Norway	Trondheim	
R242	Norway	Trondheim	
R243	Norway	Trondheim	
R244	Norway	Trondheim	
R245	Norway	Trondheim	
R246	Norway	Trondheim	
R247	Norway	Trondheim	
R248	Norway	Tromsø	
R249	Norway	Trondheim	
R250	Norway	Tromsø	
R251	Norway	Tromsø	
R252	Norway	Tromsø	
R253	Norway	Tromsø	
R254	Norway	Tromsø	
R255	Norway	Tromsø	
R256	Norway	Tromsø	
R257	Norway	Tromsø	
227 respondents	5 countries	17 cities	9 months

6.4 Overview of interviews by interview number

Interview Number	Country	Location	Date
R1	Iceland	Reykjavik	September, 2016
R2	Iceland	Reykjavik	
R3	Iceland	Reykjavik	
R4	Iceland	Reykjavik	
R5	Iceland	Reykjavik	
R6	Iceland	Reykjavik	
R7	Iceland	Reykjavik	
R8	Iceland	Reykjavik	
R9	Iceland	Reykjavik	
R10	Iceland	Reykjavik	
R11	Iceland	Reykjavik	
R12	Iceland	Reykjavik	
R13	Iceland	Reykjavik	
R14	Iceland	Reykjavik	October 2016
R15	Iceland	Reykjavik	
R16	Iceland	Reykjavik	
R17	Iceland	Reykjavik	
R18	Iceland	Reykjavik	
R19	Iceland	Reykjavik	
R20	Iceland	Reykjavik	
R21	Iceland	Reykjavik	
R22	Iceland	Reykjavik	
R23	Iceland	Akureyri	
R24	Iceland	Akureyri	
R25	Iceland	Akureyri	
R26	Iceland	Akureyri	
R27	Iceland	Akureyri	
R28	Iceland	Akureyri	
R29	Iceland	Reykjavik	
R30	Sweden	Stockholm	November 2016
R31	Sweden	Stockholm	
R32	Sweden	Stockholm	
R33	Sweden	Stockholm	
R34	Sweden	Stockholm	
R35	Sweden	Stockholm	
R36	Sweden	Stockholm	

R37	Sweden	Stockholm	
R38	Sweden	Stockholm	
R39	Sweden	Stockholm	
R40	Sweden	Stockholm	
R41	Sweden	Stockholm	
R42	Sweden	Stockholm	
R43	Sweden	Stockholm	
R44	Sweden	Gothenburg	
R45	Sweden	Gothenburg	
R46	Sweden	Gothenburg	
R47	Sweden	Gothenburg	
R48	Sweden	Gothenburg	
R49	Sweden	Gothenburg	
R50	Sweden	Gothenburg	
R51	Sweden	Gothenburg	
R52	Sweden	Gothenburg	
R53	Sweden	Gothenburg	
R54	Sweden	Gothenburg	
R55	Sweden	Gothenburg	
R56	Sweden	Gothenburg	
R57	Sweden	Gothenburg	
R58	Sweden	Gothenburg	
R59	Sweden	Gothenburg	
R60	Sweden	Gothenburg	
R61	Sweden	Gothenburg	
R62	Sweden	Malmo/Lund	
R63	Sweden	Malmo/Lund	
R64	Sweden	Malmo/Lund	
R65	Sweden	Malmo/Lund	
R66	Sweden	Stockholm	
R67	Sweden	Stockholm	
R68	Sweden	Stockholm	
R69	Sweden	Malmo/Lund	
R70	Sweden	Stockholm	December 2016
R71	Sweden	Malmo/Lund	
R72	Denmark	Other	January 2017
R73	Denmark	Copenhagen	
R74	Denmark	Copenhagen	February 2017
R75	Denmark	Copenhagen	
R76	Denmark	Copenhagen	

R77	Denmark	Copenhagen	
R78	Denmark	Copenhagen	
R79	Denmark	Copenhagen	
R80	Denmark	Copenhagen	
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R84	Denmark	Copenhagen	
R85	Denmark	Copenhagen	
R86	Denmark	Copenhagen	
R87	Denmark	Copenhagen	
R88	Denmark	Copenhagen	
R89	Denmark	Copenhagen	
R90	Denmark	Copenhagen	
R91	Denmark	Copenhagen	
R92	Denmark	Copenhagen	
R93	Denmark	Copenhagen	
R94	Denmark	Copenhagen	
R95	Denmark	Copenhagen	
R96	Denmark	Copenhagen	
R97	Denmark	Copenhagen	
R98	Denmark	Copenhagen	
R99	Denmark	Copenhagen	
R100	Denmark	Copenhagen	
R101	Denmark	Aarhus	
R102	Denmark	Aarhus	
R103	Denmark	Other	
R104	Denmark	Aarhus	
R105	Denmark	Aarhus	
R106	Denmark	Aarhus	
R107	Denmark	Aarhus	
R108	Denmark	Aalborg	
R109	Denmark	Aalborg	
R110	Denmark	Aalborg	
R111	Denmark	Aalborg	
R112	Denmark	Aalborg	
R113	Denmark	Copenhagen	March 2017
R114	Denmark	Aalborg	
R115	Denmark	Copenhagen	
R116	Denmark	Aalborg	

R117	Finland	Helsinki	
R118	Finland	Helsinki	
R119	Finland	Helsinki	
R120	Finland	Helsinki	
R121	Finland	Helsinki	
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R123	Finland	Helsinki	
R124	Finland	Helsinki	
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R126	Finland	Helsinki	
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R136	Finland	Helsinki	
R137	Finland	Helsinki	
R138	Finland	Helsinki	
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R142	Finland	Helsinki	
R143	Finland	Helsinki	
R144	Finland	Helsinki	
R145	Finland	Tampere	
R146	Finland	Tampere	
R147	Finland	Tampere	
R148	Finland	Tampere	
R149	Finland	Tampere	
R150	Finland	Tampere	
R151	Finland	Tampere	
R152	Finland	Tampere	
R153	Finland	Tampere	
R154	Finland	Helsinki	
R155	Finland	Tampere	
R156	Finland	Oulu	

R157	Finland	Oulu	
R158	Finland	Oulu	
R159	Finland	Oulu	
R160	Finland	Oulu	
R161	Finland	Oulu	
R162	Finland	Helsinki	
R163	Finland	Oulu	
R164	Finland	Oulu	
R165	Finland	Oulu	
R166	Finland	Oulu	
R167	Norway	Oslo	April 2017
R168	Norway	Oslo	
R169	Norway	Oslo	
R170	Norway	Oslo	
R171	Norway	Oslo	
R172	Norway	Oslo	
R173	Norway	Oslo	
R174	Norway	Oslo	
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R206	Norway	Oslo	
R207	Norway	Oslo	
R208	Norway	Oslo	
R209	Norway	Trondheim	May 2017
R210	Norway	Trondheim	
R211	Norway	Trondheim	
R212	Norway	Trondheim	
R213	Norway	Trondheim	
R214	Norway	Trondheim	
R215	Norway	Trondheim	
R216	Norway	Trondheim	
R217	Norway	Trondheim	
R218	Norway	Trondheim	
R219	Norway	Trondheim	
R220	Norway	Trondheim	
R221	Norway	Trondheim	
R222	Norway	Trondheim	
R223	Norway	Tromsø	
R224	Norway	Tromsø	
R225	Norway	Tromsø	
R226	Norway	Tromsø	
R227	Norway	Tromsø	
227 interviews	5 countries	17 cities	9 months

6.5 Survey script

2016-2017 Nordic Vehicle Preferences Survey

Part 1: Vehicle Background & Preferences

Welcome to the 2016-2017 Nordic Vehicle Preferences Survey!

Thank you for taking the time to fill in our survey. We will be asking you several questions on your preferences regarding cars. Your responses will be kept confidential and your participation is voluntary. If you should come to any question you prefer not to answer, please move on to the next. We estimate that the survey will take about 10 to 15 minutes.

Parts of this survey will discuss a concept called vehicle-to-grid. To describe it briefly, **vehicle-to-grid** (V2G) technology allows you to not only **charge** an electric vehicle (EV), but it also lets you **store** electricity in its battery and **return** it back to the electricity grid when the vehicle is connected at your home, work or public charging station. The ability to store and return electricity gives the option to **(1)** balance the electricity grid at times of system stress (if for example electricity demand is too high), and it also has the potential to **(2)** earn money for the car owner, if you return electricity or store it in your vehicle. However, the vehicle owners have to plan their trips before driving and communicate these trips with an independent company (via a mobile app or online system) so the electricity system and the car owner always know how much electricity is in the vehicle and how much is required from it. Generally speaking, it is estimated that vehicle owners could earn around €200 a month in revenue.

With this survey we hope to better understand people's vehicle preferences. Your responses will help us make better and more accurate policy recommendations for the future of transportation in the Nordic region. If you have any questions or comments regarding the survey, please contact us at V2G.research@btech.au.dk.

Do you currently own or drive a car?

Yes

No

How long have you had a full driver's license?

Less than a year

Between 1 and 5 years

Between 5 and 10 years

More than 10 years

I don't currently have a driver's license

How many kilometers do you usually drive in a car every day?

≤ 20 km

20~50 km

50~80 km

80~100 km

≥ 100 km

I don't regularly drive a car

Over the last year, what was the longest trip you took by car? *Please enter your best estimate as a whole number, in kilometers. Include rest stops, but not overnight stays.*

In an average month, which of the following modes of transportation do you use the most? *Please only the rank your top three choices.*

Bicycle

Bus

Car

Metro/Tram

Scooter/Moped

Train

Walking

Other (please specify):

If you were to buy a car, which type of car are you most likely to buy next?

Economy or City Car

Family Car or Multi-Purpose Vehicle (MPV)

Luxury or Sports Car

Sports Utility Vehicle (SUV)

Pickup Truck

Other (please specify)

I'm not planning on buying a car

When do you expect to buy your next car?

Within the next year

Between 1 and 5 years from now

Between 5 and 10 years from now

More than 10 years from now

Not sure/Don't know

Don't expect to purchase another vehicle

How much do you expect to spend on your next car?

≤ €10,000

€10,001 to €20,000

€20,001 to €30,000

€30,001 to €40,000

€40,001 to €50,000

≥ €50,000

Where do you expect to buy your next car?

Brand new (from a dealership)

Previously owned/used (from a dealership)

Previously owned/used (from another source)

Not sure/Don't know

Other (please specify)

Have you ever driven an electric vehicle? *Please only include fully electric plug-in vehicles.*

Yes

No

Not sure/Don't know

Have you ever owned an electric vehicle? *Please only include fully electric plug-in vehicles.*

Yes, I currently own an electric vehicle

Yes, I used to own an electric vehicle, but no longer do

No, I have never owned an electric vehicle

In the previous question you stated that you currently own an electric vehicle. What was the main reason you switched from your previous mode of transportation to an electric vehicle?

Financial savings/lower cost of operation

Environmental benefits

Interest in new technology

Better performance

Government incentives

Other (please specify)

What is the main disadvantage of driving your electric vehicle?

Limited range of electric vehicle

Recharging time of battery

Lack of public charging infrastructure

Cost of ownership

Comfort and/or size of electric vehicle (e.g., too small for family, etc.)

Other

In the previous question, you said you previously owned an electric vehicle but not longer do. What was the main reason you switched from an electric vehicle to another mode of transport?

Limited range of electric vehicle

Recharging time of battery

Lack of public charging infrastructure

Cost of ownership

Comfort and/or size of electric vehicle (e.g. too small for family, etc.)

Prefer not to say

Other

In the previous question, you said you have never owned an electric vehicle. The next time you purchase a vehicle, how interested or uninterested would you be in purchasing an electric vehicle?

Very interested

Somewhat interested

Neither interested or uninterested

Somewhat uninterested

Very uninterested

In the previous question you stated that you are interested in considering to purchase an electric vehicle. What is the main reason why you would consider purchasing an electric vehicle?

Financial savings/lower cost of operation

Environmental benefits

Interest in new technology

Better performance

Government incentives

Other (please specify)

In the previous question you stated that you are uninterested in purchasing an electric vehicle. What is the main reason why you are uninterested in electric vehicles?

Limited range of electric vehicle

Recharging time of battery

Lack of public charging infrastructure

Cost of ownership

Comfort and/or size of electric vehicle (e.g., too small for family, etc.)

Prefer not to say

Other (please specify)

Before today, have you ever heard of the concept vehicle-to-grid (V2G)?

Yes

No

Not sure/Don't know

Part 2: Vehicle Preferences

Thank you for your responses so far. For the next section, we will ask you about the relative importance of various characteristics of the vehicle.

When purchasing a vehicle, how important or unimportant is the **speed and acceleration** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **size and comfort** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **design and style** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **ease of operation** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **safety** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **technological reliability** of the vehicle?

Very important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **fuel economy and the financial savings** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant is the **price** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When purchasing a vehicle, how important or unimportant are the **environmental attributes** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

Thank you for your responses so far. We would now like you to think specifically about **electric vehicles**. If you were to consider purchasing an electric vehicle, please rank the following attributes on their relative importance to you.

When considering an electric vehicle, how important or unimportant is the **driving range** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When considering an electric vehicle, how important or unimportant is the **battery life** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When considering an electric vehicle, how important or unimportant is the **availability of public chargers**?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When considering an electric vehicle, how important or unimportant is the **duration of charging** of the vehicle?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

When considering an electric vehicle, how important or unimportant is it that the vehicle is **vehicle-to-grid (V2G) capable**, that is, being able to not only charge, but also store and return electricity from the vehicle to your home and/or electricity grid?

Very Important

Somewhat Important

Neither Important or Unimportant

Somewhat Unimportant

Very Unimportant

Part 4: Demographics

Thank you for your participation, you're almost done! For the final section, we would now like to ask you some demographic questions. This information will help us analyze the results of our survey, which helps us to make better policy recommendations.

What is your gender?

Male

Female

Other

Prefer not to say

What is your current age? *Please enter your current age as a whole number below.*

Including yourself, how many members are living within your household?

Number of Adults

Number of Children

How many cars do you have in your household?

How important is the environment to you?

Extremely Important

Very Important

Somewhat Important

Slightly Important

Not At All Important

Which of the following best describes the area you live in?

Rural

Suburban

Urban

What is your highest level of completed education?

Secondary School

Undergraduate Degree

Postgraduate Degree

Prefer not to say

Other (please specify)

Which best describes your type of occupation?

Private sector

Non-profit non-governmental organization

Government

Academic institution

Retired

Unemployed

Student

Prefer not to say

Other (please specify)

Over the past years, have you done any of the following:

	Yes	No
Installed energy efficient appliances in my house	◯	◯
Invested in a solar panel or other sustainable energy system	◯	◯
Changed my diet to eat less meat or more local products	◯	◯
Increased my waste recycling efforts	◯	◯
Decreased my household water use	◯	◯

Which of the following would best describe your political leanings?

Socialist/Green

Social Democrat

Christian Democrat/Conservative

Liberal

Prefer not to say

Other

What is your current after-tax yearly household income?

≤ €10.000

€10.001 to €30.000

€30.001 to €50.000

€50.001 to €70.000

€70.000 to €90.000

> €90.000

Prefer not to answer

What is your current country of residence?

Denmark

Finland

Iceland

Norway

Sweden

Other (please specify)

Survey Conclusion

This concludes our survey. We really appreciate your responses as well as your time. If you have any questions or comments regarding the survey, please contact us at V2G.research@btech.au.dk. For further information regarding our project, please visit our website.

Thank you!

Contact us at V2G.research@btech.au.dk // Center for Energy Technologies, Birk Centerpark 15, Aarhus University, Herning 7400 DK

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6.6 Dealership visits

Visits conducted across the five Nordic countries of Denmark, Finland, Iceland, Norway and Sweden. Note: V1= Visit 1. EV = Electric Vehicle.

No. Visit	Country	Brand specificity	Salesperson 's Gender	EV Brand Availability	Date
V1	Iceland	Multibrand	Male	EV Certified	Oct-16
V2	Iceland	Brand Specific	Male	Non-EV Certified	Oct-16
V3	Iceland	Multibrand	Male	EV Certified	Oct-16
V4	Iceland	Multibrand	Male	EV Certified	Oct-16
V5	Iceland	Multibrand	Male	Non-EV Certified	Oct-16
V6	Iceland	Brand Specific	Male	Non-EV Certified	Oct-16
V7	Iceland	Multibrand	Male	EV Certified	Oct-16
V8	Iceland	Brand Specific	Female	Non-EV Certified	Oct-16
V9	Iceland	Multibrand	Male	EV Certified	Oct-16
V10	Iceland	Multibrand	Male	EV Certified	Oct-16
V11	Iceland	Multibrand	Male	EV Certified	Oct-16
V12	Iceland	Multibrand	Male	Non-EV Certified	Oct-16
V13	Iceland	Multibrand	Male	EV Certified	Oct-16
V14	Iceland	Multibrand	Male	Non-EV Certified	Oct-16
V15	Iceland	Multibrand	Male	Non-EV Certified	Oct-16
V16	Iceland	Multibrand	Male	Non-EV Certified	Oct-16
V17	Iceland	Brand Specific	Male	Non-EV Certified	Oct-16
V18	Iceland	Multibrand	Male	EV Certified	Oct-16
V19	Sweden	Brand Specific	Male	Non-EV Certified	Nov-16
V20	Sweden	Brand Specific	Male	EV Certified	Nov-16
V21	Sweden	Brand Specific	Female	Non-EV Certified	Nov-16

V22	Sweden	Brand Specific	Male	EV Certified	Nov-16
V23	Sweden	Brand Specific	Male	EV Certified	Nov-16
V24	Sweden	Multibrand	Male	EV Certified	Nov-16
V25	Sweden	Multibrand	Male	Non-EV Certified	Nov-16
V26	Sweden	Multibrand	Male	Non-EV Certified	Nov-16
V27	Sweden	Multibrand	Male	Non-EV Certified	Nov-16
V28	Sweden	Multibrand	Male	Non-EV Certified	Nov-16
V29	Sweden	Multibrand	Male	EV Certified	Nov-16
V30	Sweden	Multibrand	Male	Non-EV Certified	Nov-16
V31	Sweden	Brand Specific	Male	EV Certified	Nov-16
V32	Sweden	Brand Specific	Male	EV Certified	Nov-16
V33	Sweden	Brand Specific	Male	Non-EV Certified	Nov-16
V34	Sweden	Brand Specific	Male	Non-EV Certified	Nov-16
V35	Sweden	Brand Specific	Female	Non-EV Certified	Nov-16
V36	Sweden	Brand Specific	Male	Non-EV Certified	Nov-16
V37	Sweden	Brand Specific	Male	EV Certified	Nov-16
V38	Sweden	Brand Specific	Male	Non-EV Certified	Nov-16
V39	Sweden	Brand Specific	Male	EV Certified	Nov-16
V40	Sweden	Brand Specific	Male	EV Certified	Nov-16
V41	Sweden	Brand Specific	Male	EV Certified	Nov-16
V42	Sweden	Brand Specific	Male	EV Certified	Nov-16
V43	Sweden	Brand Specific	Male	EV Certified	Nov-16

V44	Denmark	Multibrand	Male	EV Certified	Feb-17
V45	Denmark	Brand Specific	Female	EV Certified	Feb-17
V46	Denmark	Brand Specific	Male	EV Certified	Feb-17
V47	Denmark	Brand Specific	Male	Non-EV Certified	Feb-17
V48	Denmark	Multibrand	Male	EV Certified	Feb-17
V49	Denmark	Multibrand	Male	EV Certified	Feb-17
V50	Denmark	Brand Specific	Male	EV Certified	Feb-17
V51	Denmark	Multibrand	Male	EV Certified	Feb-17
V52	Denmark	Brand Specific	Male	Non-EV Certified	Feb-17
V53	Denmark	Brand Specific	Male	EV Certified	Feb-17
V54	Denmark	Brand Specific	Male	Non-EV Certified	Feb-17
V55	Denmark	Multibrand	Male	EV Certified	Feb-17
V56	Denmark	Brand Specific	Male	EV Certified	Feb-17
V57	Denmark	Multibrand	Male	Non-EV Certified	Feb-17
V58	Denmark	Brand Specific	Male	EV Certified	Feb-17
V59	Denmark	Brand Specific	Male	EV Certified	Feb-17
V60	Denmark	Multibrand	Male	EV Certified	Feb-17
V61	Denmark	Multibrand	Male	Non-EV Certified	Feb-17
V62	Denmark	Brand Specific	Male	EV Certified	Feb-17
V63	Denmark	Brand Specific	Male	EV Certified	Jun-17
V64	Denmark	Multibrand	Male	Non-EV Certified	Jun-17
V65	Denmark	Brand Specific	Male	EV Certified	Jun-17
V66	Denmark	Multibrand	Male	EV Certified	Jun-17
V67	Denmark	Brand Specific	Male	Non-EV Certified	Jun-17

V68	Denmark	Brand Specific	Male	Non-EV Certified	Jun-17
V69	Denmark	Brand Specific	Male	EV Certified	Jun-17
V70	Denmark	Brand Specific	Male	EV Certified	Jun-17
V71	Denmark	Multibrand	Male	Non-EV Certified	Jun-17
V72	Denmark	Multibrand	Male	EV Certified	Jun-17
V73	Denmark	Multibrand	Male	EV Certified	Jun-17
V74	Denmark	Brand Specific	Male	EV Certified	Jun-17
V75	Denmark	Brand Specific	Male	Non-EV Certified	Jun-17
V76	Denmark	Brand Specific	Male	Non-EV Certified	Jun-17
V77	Denmark	Brand Specific	Male	EV Certified	Jun-17
V78	Denmark	Brand Specific	Male	EV Certified	Jun-17
V79	Finland	Multibrand	Male	EV Certified	Mar-17
V80	Finland	Brand Specific	Male	EV Certified	Mar-17
V81	Finland	Multibrand	Male	EV Certified	Mar-17
V82	Finland	Brand Specific	Male	EV Certified	Mar-17
V83	Finland	Multibrand	Male	Non-EV Certified	Mar-17
V84	Finland	Brand Specific	Male	Non-EV Certified	Mar-17
V85	Finland	Multibrand	Male	EV Certified	Mar-17
V86	Finland	Multibrand	Male	EV Certified	Mar-17
V87	Finland	Multibrand	Male	Non-EV Certified	Mar-17
V88	Finland	Brand Specific	Female	EV Certified	Mar-17
V89	Finland	Brand Specific	Male	EV Certified	Mar-17

V90	Finland	Brand Specific	Female	EV Certified	Mar-17
V91	Finland	Multibrand	Male	EV Certified	Mar-17
V92	Finland	Brand Specific	Male	EV Certified	Mar-17
V93	Finland	Brand Specific	Male	EV Certified	Mar-17
V94	Finland	Multibrand	Male	EV Certified	Mar-17
V95	Finland	Brand Specific	Male	Non-EV Certified	Mar-17
V96	Finland	Brand Specific	Male	EV Certified	Mar-17
V97	Finland	Multibrand	Male	Non-EV Certified	Mar-17
V98	Finland	Brand Specific	Male	Non-EV Certified	Mar-17
V99	Finland	Multibrand	Male	EV Certified	Mar-17
V100	Finland	Brand Specific	Male	EV Certified	Mar-17
V101	Finland	Multibrand	Male	EV Certified	Mar-17
V102	Finland	Multibrand	Male	EV Certified	Mar-17
V103	Norway	Brand Specific	Male	EV Certified	Apr-17
V104	Norway	Multibrand	Male	EV Certified	Apr-17
V105	Norway	Brand Specific	Male	EV Certified	Apr-17
V106	Norway	Brand Specific	Male	EV Certified	Apr-17
V107	Norway	Multibrand	Male	EV Certified	Apr-17
V108	Norway	Brand Specific	Male	Non-EV Certified	Apr-17
V109	Norway	Multibrand	Male	Non-EV Certified	Apr-17
V110	Norway	Brand Specific	Male	EV Certified	Apr-17
V111	Norway	Brand Specific	Male	EV Certified	Apr-17

V112	Norway	Multibrand	Male	EV Certified	Apr-17
V113	Norway	Brand Specific	Male	EV Certified	Apr-17
V114	Norway	Brand Specific	Male	EV Certified	Apr-17
V115	Norway	Brand Specific	Male	EV Certified	Apr-17
V116	Norway	Brand Specific	Male	EV Certified	Apr-17
V117	Norway	Brand Specific	Female	EV Certified	Apr-17
V118	Norway	Multibrand	Male	EV Certified	Apr-17
V119	Norway	Multibrand	Male	Non-EV Certified	Apr-17
V120	Norway	Brand Specific	Male	Non-EV Certified	Apr-17
V121	Norway	Multibrand	Male	EV Certified	May-17
V122	Norway	Brand Specific	Male	EV Certified	May-17
V123	Norway	Brand Specific	Male	Non-EV Certified	May-17
V124	Norway	Brand Specific	Male	EV Certified	May-17
V125	Norway	Brand Specific	Male	EV Certified	May-17
V126	Norway	Brand Specific	Male	EV Certified	May-17

6.7 Interviews experts for article 1

Record of interviewees across the five Nordic countries. Note: EVSE = Electric Vehicle Supply Equipment. OEM = Automotive Original Equipment Manufacturer. R01 = Respondent 01.

No. Interview	Type	Interviewee's Gender	Country	Date
R01	Importer	Male	Iceland	Oct-16
R02	Association	Male	Iceland	Oct-16
R03	Importer	Male	Iceland	Oct-16
R04	Consulting	Male	Iceland	Oct-16
R05	Importer	Male	Iceland	Oct-16
R06	Association	Male	Iceland	Oct-16
R07	Importer	Male	Iceland	Oct-16
R08	EVSE	Male	Sweden	Nov-16
R09	Association	Male	Sweden	Nov-16
R10	OEM	Male	Sweden	Nov-16
R11	Research	Male	Sweden	Nov-16
R12	Investment	Male	Sweden	Nov-16
R13	EVSE	Female	Sweden	Nov-16
R14	OEM	Female	Denmark	Feb-17
R15	EVSE	Male	Denmark	Feb-17
R16	OEM	Male	Denmark	Feb-17
R17	Mobility	Male	Denmark	Feb-17
R18	OEM	Male	Finland	Mar-17
R19	Consulting	Male	Finland	Mar-17
R20	Utility	Male	Finland	Mar-17
R21	Consulting	Male	Finland	Mar-17
R22	OEM	Male	Norway	Apr-17
R23	Association	Male	Norway	Apr-17
R24	OEM	Female	Norway	Apr-17
R25	OEM	Male	Norway	Apr-17
R26	Association	Male	Norway	Apr-17
R27	Importer	Male	Norway	Apr-17
R28	OEM	Female	Norway	Apr-17
R29	Research	Male	Norway	May-17
R30	Importer	Male	Norway	May-17