Managing the Risks of Wind Farms in Forested Areas: Design Principles for Northern Europe

Industrial PhD dissertation: 4135-00033B

Peter Enevoldsen

Acknowledgements

I would like to express my sincere gratitude to my advisor Benjamin K. Sovacool for the continuous support of my research, for his motivation, vast knowledge, and for always encouraging me to provoke the "truth" and existing paradigms. His guidance made me a real researcher and I now truly know the meaning of exploiting time. In continuation, I would like to thank and explicate my appreciation to my company advisor Thorben G. Nielsen for guiding me, for the constant encouragement and most of all for allowing me to dream and supporting me in the realization of these dreams. I deeply thank my company co-advisor Kell Øhlenschlæger for his immense support and supervision during the entire Ph.D. I could not have imagined having a better team of advisors and mentors for my research.

My sincere thanks also goes to the Siting team members in Siemens Gamesa Renewable Energy, and a special gratitude to the Global Siting Team who provided me an opportunity to join their team. Without their precious support, questions, and verification of research results it would not have been possible to conduct this study.

I thank the researchers at Aarhus University for the stimulating discussions, with a special thanks to Anders Frederiksen and Torben Tambo for their continuous support from the very first time I mentioned my dream of doing research. Also I thank Mark Z. Jacobson for hosting me at Stanford University, I enjoy witnessing the mark our research leaves on the battle against climate changes.

In particular, I am grateful to Ebba Dellwik from DTU for endless talks, inspiration, and for enlightening me in the art of forest research. The same goes for Johan Arnqvist from Uppsala University for introducing me to the endless opportunities and challenges of researching wind conditions in and above forests in Northern Europe. I sincerely expect our research to continue and bloom even further.

I would also like to thank all my co-authors, as each of you have taught me new things and surely made me the researcher I am today. I believe in interdisciplinary teamwork, and I hope that reflects in our results. A special thanks goes to Peng Hou and Scott Victor Valentine, who has inspired and taught me how to further develop my research portfolio.

Last but definitely not least, as words cannot express how much I would like to thank my family for believing in me spiritually throughout this research and especially in my life in general.

Henriette, we did it!

Executive Summary

Research focusing on the risks associated with onshore wind project development is an increasing phenomenon, due to the growth of onshore wind power, both in installed capacity and geographically, with installations in new continents and markets. In Northern Europe, wind power, and thereby the wind industry, has dominated the power systems for decades, leading to novel innovations of wind turbine designs, wind farm configurations, and, ultimately, locations. Wind projects started to be developed in forests for simple reasons: first because of the forest coverage in Sweden, where it is almost impossible to develop an onshore wind farm without the interference of forests, and second, because of the growth in the installed number of onshore wind turbines in Northern Europe, which leads to social opposition as a response to the noise and flicker impact from wind turbines upon their human neighbours. At the same time, support systems made wind power profitable in this region of the world, which is why land owners raised the cost of acquiring suitable land. Simultaneously, and partly as a response to these events, wind turbines were growing in size, which: a) allowed the blades to spin in forests without interacting directly with the tree canopies, and b) increased the impact on humans, which initially forced wind farms into the forests.

However, the siting of wind turbines in forested areas entails other challenges and risks, which have not yet been addressed by academia or the industry. The wind flows above forest canopies are harder to estimate, and especially if the forest formation is heterogeneous with clearing and different tree types and heights. Furthermore, the deployment of wind farms in forests involves different risks, as social opposition occurs for a variety of reasons, and the environmental impact of deforestation versus the increased wind speeds when removing remains to be studied in depth. It is thus considered vital for future wind power development to address these risks, and furthermore, to address these risks using a holistic perspective including measures from business, social science, and engineering. To examine these objectives and thereby the design principles which are required to manage the risks of wind turbines in forested areas in Northern Europe, the following three research questions are introduced:

Research Question 1: *What are the specifications of wind projects in forested areas?*

Research Question 2: *How can the risks associated with the siting of wind turbines be limited?*

Research Question 3: *What is the best approach to managing the risks of wind project development in Northern European forests?*

In answering these research questions, more than 15 peer-reviewed publications have been submitted, where six of the research articles are introduced in this dissertation. Research Question 1 is encompassed by two journal articles entitled: 1) *Do onshore and offshore wind farm development patterns differ?* and 2) *Onshore wind energy in Northern European forests: Reviewing the Risks* Research Question 2 encompasses two journal articles entitled: 3) *Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France* and 4) *From Lidar scans to roughness maps for wind resource modeling in forested areas*. Research Question 3 encompasses two journal articles entitled: 5) *A Socio-Technical Framework for Examining the Consequences of Deforestation: A Case Study of Wind Project Development in Northern Europe* and 6) *Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden.*

The research questions and articles adopt a research strategy of applying mixed methods to cover the complexity of socio-technical studies. The interdisciplinary requirements of bringing social science and engineering together have resulted in holistic output applicable for all stakeholders in the wind industry, and, at the same time, results and recommendations which, due to their interdisciplinary nature, are expected to fulfill the need of managing the risks in the siting of wind turbines in Northern European forests.

The first journal article (*Do onshore and offshore wind farm development patterns differ?*) answering Research Question 1 (*What are the specifications of wind projects in forested areas?*) sought to differentiate wind farms in forests from the two main wind farm configurations: Onshore and Offshore. The forest configuration was validated by dividing and examining the performance from operating wind turbines using data from more than 1,000 MWs of installed wind power. The research was carried out using the operational data from the three wind farm configurations (Onshore, Offshore, and Forest) and testing it using four preconceptions and four hypotheses based on measures such as the typical size of each wind farm configuration, the effectiveness (MWh/Installed MW) of each configuration, and the technological progress and learning effects of each configuration.

While empirically testing previous literature on onshore versus offshore wind power performance, the study also revealed that wind turbines located in forested areas could be capable of reaching a similar power production to that of offshore wind turbines without the additional costs associated with the construction of offshore projects. Furthermore, it was discussed why onshore wind turbines in forested areas had different performance patterns from the other onshore wind turbines, which was primarily explained by the novelty of wind turbines used in forests with greater rotor diameters and increased hub heights. Conclusively, the forest configuration could be validated as a separate configuration; however, in order to understand the risks associated with wind project development in forested areas, a second paper was also carried out to finalize the answer for Research Question 1.

The second journal article (*Onshore wind energy in Northern European forests: Reviewing the risks.*) answering Research Question 1 (*What are the specifications of wind projects in forested areas?*) aimed at conducting the most comprehensive literature review on risks associated with wind power in forested areas throughout a wind project's lifecycle. The paper presented a risk framework, which structured the search for literature, and at the same time introduced a structural approach to examine a wind project through ten risk parameters divided into three phases of the wind project lifecycle from pre-construction to decommission.

One of the main research outputs was an overview of which risks have been covered by literature, which were only two of the ten discovered risk parameters, albeit still with remarkable omissions which defined the later research of the entire project. Another output was an overview of the specific risks for each of the targeted countries in Northern Europe, with Denmark, Norway, Sweden, and the UK analyzed individually for all ten parameters. In addition, the trends in literature for each country and for Northern Europe as a whole were compared to the development of wind power. This multidimensional and novel approach for conducting comparative studies between the development of a technology and the development of scholarship indicated that trends in the literature imply that the community and wind industry have shifted in what they regard as important risk parameters, and that the expansion of wind power to forested areas is introducing new topics of risk. It was revealed that

social opposition is a threat, however, perhaps a bit less severe in forested areas. The most severe risk was determined as the resource assessment of wind conditions over forest canopies, which called for a separate study of approaches and potential solutions.

Research Question 1 has been answered by the two articles, where the first article emphasizes the importance of defining forestry as an individual configuration for wind power by revealing and examining parameters in comparative studies driven by the testing of hypotheses. The second article provides an overview of the risks previously covered by literature. The two remaining research questions are taxonomic developing and thereby investigating the risks and later how to manage such risks.

The third journal article (*Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France)* answered Research Question 2 (*How can the risks associated with the siting of wind turbines be limited?)* and sought to understand the general mechanisms behind social opposition of onshore wind projects. The second journal article revealed that while social opposition is less likely to occur for wind projects in forested areas, the reasons for triggering such opposition remains the same across all onshore projects. The study was carried out by interviewing stakeholders in the French wind energy market, meanwhile analyzing the daily challenges of a wind project developer. The findings were supported by a literature review, in order to establish an overview of reasons for social opposition, and activities and actions to decrease the opposition. The constructed guidelines on how to increase the likelihood of social acceptance for onshore wind project development has later been applied in Research Question 3, in order to map the impact of social opposition on wind power expansion in forested areas. This article has therefore served as the foundation for later research. The second journal article revealed that although social opposition is a risk for wind project development in forested areas, the most severe risk remains the estimation of wind flows above forest canopies.

Therefore, the fourth paper (*From Lidar scans to roughness maps for wind resource modeling in forested areas)* summarizes a number of the publications related to this project, which have been investigating previous and current approaches for the estimation of wind conditions in and above forest canopies, and also including a separate methodology for conducting issues such as resource assessment. The paper introduces the optimized roughness approach (ORA), which is a method for converting tree heights of either evergreen coniferous or broadleaved deciduous trees into roughness lengths and maps applicable in all software programs for wind resource assessments. ORA is based on a combination of the roughness length (Z_0) approach of applying (1)

(1) $$Z_0 = 0.3 \cdot (tree\ height - Z_d)$$

and a displacement height of (2)

(2) $$(Z_d)\ of\ Z_d = 0.66 * tree\ height$$

resulting in the best fit for evergreen coniferous tree types, with a mean error of 2.18% when tested against 22 meteorological masts using WAsP and WindPRO. The paper also tested four popular online sources for roughness maps, and found that all provided misleading results, which could have a hugely negatively impact upon a business case or even result in severe fatigue loads on vital wind

turbine components because of an underestimation of the impact from the forests. Conclusively, the approach was tested against various CFD models, leading to the conclusion that the wind industry needs to provide better data input such as laser scanned leaf area densities to run CFD models in forested areas.

The fifth journal article (*A Socio-Technical Framework for Examining the Consequences of Deforestation: A Case Study of Wind Project Development in Northern Europe*) answers Research Question 3 (*What is the best approach to managing the risks of siting of wind turbines in Northern European forests?*) by using the approach from ORA to simulate the impact of deforestation on four topics: Annual Energy Production, Social Opposition, Environmental Impact, and the Levelized Cost of Energy. The interdisciplinary approach to this article resulted in a validated socio-technical framework for the consequences of deforestation in Northern Europe when developing new wind projects. The framework is applicable for stakeholders in the wind industry to decide if, and potentially how, large an area to deforest. The decision is based on all four parameters, as it was revealed that the income of deforestation would increase the annual energy production, increase social opposition if the forest is natural and not industrial, have a negative impact on the environmental budget, and lower the levelized cost of energy. However, without an income the financial argument for deforestation is very limited, and would not be recommended in natural forests, due to increased social opposition and the negative impact on flora and fauna. Another interesting perspective is the impact on the fatigue loads on the wind turbine, as it was revealed that clearing 23 hectares of dense forest for a wind turbine with a hub height of 115 meters and a rotor diameter of 113 meters would most likely minimize the turbulence intensity and thereby potentially expand the lifetime of the wind turbine, which, in this case, would lead to a better environmental impact and a lower levelized cost of energy over the lifetime of the wind turbine.

The sixth and final journal article (*Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden*) in this dissertation combines all of the applied studies and output and maps the socio-technical constraints of Sweden into one interactive wind atlas using geographical information systems. The wind atlas was based on interviews with five overall Swedish stakeholder groups in the wind industry, data collection of infrastructure, buildings, and protected areas, and the development of a Swedish wind map based on an extensive wind data collection. The mapping of the wind atlas made it possible to determine where in Sweden projects are most likely to be rejected, and where the best wind resources exist. While informing stakeholders on where to develop wind farms, the wind atlas also revolutionizes the typical wind atlases, which have so far primarily focused on wind resources. However, the socio-technical wind atlas for Sweden revealed that the best wind resources are often locations with natural protected areas or a dense population. Socio-technical wind atlases can reveal which forests in a country are most appropriate for wind project development by avoiding natural areas, areas perceived as public property, and areas with homogenous forest formations.

It can be concluded that the three research questions have been answered using a range of quantitative and qualitative data collection methods, which ensures a holistic perspective on the socio-technical risks that have to be managed when siting onshore wind projects in Northern European forests. The conclusion of the dissertation and industrial PhD project 4135-00033B is that the changes of wind conditions above forest canopies can be estimated using specific methods with high-quality data input

regarding tree heights and leaf area densities. In addition, the dissertation found that the resource assessment of a site should include social values, as land use and social acceptance also impact upon the risks of succeeding with a project. These risks differ across national borders, and especially the social opposition when examining the consequences of deforestation.

Danish Summary

Der er en stigende tendens til studier, som fokuserer på risici associeret med onshore vindprojektudvikling, hvilket skyldes den eksplosive vækst af installeret onshore vindkapacitet. Den installerede vindkapacitet har ydermere ekspanderet til nye kontinenter og markeder gennem de seneste år. I årtier har vindmøller og vindindustrien været dominerende faktorer i energimarkedet i Nordeuropa, hvilket har ledt til innovationer af vindmølledesign, konfigurationer og nye geografiske lokationer for vindprojektudvikling. Udviklingen af vindprojekter i skovområder skyldes først og fremmest, at historisk attraktive vindmarkeder så som Danmark, Sverige og Storbritaninen har en høj procentdel af landoverfladen dækket af skove. Den høje procentdel skov medvirker, at det nærmest er umuligt at udvikle et vindprojekt uden at interagere med skoven. Derudover har væksten af installerede vindmøller i Nordeuropa medvirket til social opposition som et modsvar til støj– og skyggeeffekter fra vindmøllerne. Derudover har de profitable støtteordninger betydet, at landejere i lange perioder har kunne tillade sig at øge leje– og købspriserne for landjord til vindprojektudvikling. Oftest er landjord billigere i skovområder, hvor der ikke er mulighed for landbrug. En effekt af muligheden for siting i skovområder, er at vindmøllerne er vokset markant i størrelse, hvilket har betydet, at a)vingerne har kunne operere i skovområder uden at ramme trækronerne, og at b) den negative effekt på mennesket er øget, da de større vindmøller larmer mere og kan ses på længere afstand, hvilket paradoksalt nok var en af nøgleårsagerne til at flytte vindmøllerne til skovområder i første omgang.

Siting af vindmøller i skovområder involverer også andre og mere kritiske risici, som endnu ikke er blevet adresseret fra akademiske eller industrielle kilder. Vindforholdene over skovens trækroner er svære at estimere, og især såfremt at skovformationen er heterogen med lysninger og forskellige træhøjder. Ydermere vil opsætningen af vindmøller i skovområder have de konsekvenser, at social opposition opstår, og der vil være miljømæssige følger, når en eventuel skovrydning foretages.

Det anses som værende afgørende for den fremtidige vindenergiudvikling, at undersøge disse risici ved brug af et holistisk perspektiv, herunder foranstaltninger fra erhvervslivet, samfundsvidenskab og teknik. For at undersøge disse mål og dermed de designprincipper, der er nødvendige for at kontrollere og minimere risikoparametre for vindmøller i skovområder i Nordeuropa, indføres følgende tre forskningsspørgsmål:

Research Question 1: *What are the specifications of wind projects in forested areas?*

Research Question 2: *How can the risks associated with the siting of wind turbines be limited?*

Research Question 3: *What is the best approach of managing the risks of wind project development in Northern European forests?*

Gennem besvarelsen af disse forskningsspørgsmål er der leveret flere end 15 peer-reviewed publikationer, hvor seks af forskningsartiklerne introduceres i denne afhandling.

Research Question 1 består af to videnskabelige artikler : *Do onshore and offshore wind farm development patterns differ?* og *Onshore wind energy in Northern European forests: Reviewing the risks.*

Research question 2 besvares følgende gennem to videnskabelige artikler med de følgende titler: *Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France* og *From lidar scans to roughness maps for wind resource modeling in forested areas.*

 Research Question 3 besvares gennem følgende videnskabelige artikler: *A Socio-Technical Framework for Examining the Consequences of Deforestation and Wind Project Development: A Case Study of Northern Europe* og *Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden.*

Forskningsspørgsmålene og artiklerne er baseret på en forskningsstrategi, der er blevet anvendt ved hjælp af mixed methods for at dække kompleksiteten af de socio-tekniske studier. De tværfaglige krav til at sammenbringe samfundsvidenskab og teknik har resulteret i et holistisk udbytte, med resultater dækkende for alle interessenter i vindindustrien, og samtidig resultater og anbefalinger, som på grund af den tværfaglige karakter forventes at opfylde behovet for at styre risiciene i placeringen af vindmøller i nordeuropæiske skovområder

Den første videnskabelige artikel (*Do onshore and offshore wind farm development patterns differ?)* besvarer research question 1 (*What are the specifications of wind projects in forested areas?*) og søger at udforske og determinere forskellene mellem vindprojekter i skove og vindprojekter lokaliseret offshore eller på landjord uden skove.

Skovkonfigurationen for vindprojekter blev valideret ved at adskille og undersøge præstationen af vindmøller ved brug af data fra mere end 1.000 MW installeret vindkraft. Forskningen blev udført ved brug af operationelle data fra de tre vindmøllekonfigurationer (Onshore, Offshore og Forest). Der blev udført eksperimenter ved hjælp af fire hypoteser baseret på foranstaltninger, så som den typiske størrelse af hver vindmølleparkkonfiguration, effektiviteten (MWh / Installeret MW) for hver konfiguration, og de teknologiske fremskridt og læringseffekter for hver konfiguration. Samtidig med en empirisk afprøvning af tidligere litteratur omfattende onshore versus offshore vindenergi viste undersøgelsen også, at vindmøller beliggende i skovområder kunne være i stand til at nå en tilsvarende energiproduktion som offshore vindmøller uden de yderligere omkostninger, som er forbundet med opførelse af offshoreprojekter. Desuden blev det diskuteret, hvorfor vindmøller i skovområder havde forskellige præstationsmønstre fra de andre landvindmøller, hvilket primært blevet forklaret via de nye vindmøller med større rotordiameter og øgede navhøjder, der anvendes i skove. Konklusivt kunne skovkonfigurationen valideres som en separat vindenergikonfiguration, men samtidig blev det afsløret at flere hypoteser behøver at blive testet, hvorfor der blev udført et yderligere studie for at færdiggøre svaret på Research Question 1.

Den anden videnskabelige artikel *(Onshore wind energy in Northern European forests: Reviewing the risks.)* besvarer Research Question 1 ved at gennemføre det mest omfattende litteraturstudie vedrørende risici forbundet med vindkraft i skovområder gennem en vindmølleparks livscyklus anno 2016. Artiklen præsenterede en risikovurdering, som strukturerede litteratursøgningen og samtidig introducerede en strukturel tilgang til at undersøge et vindprojekt gennem ti risikoparametre opdelt i tre faser af vindprojektets livscyklus fra planlægning til afvikling.

Et af de vigtigste forskningsresultater var et overblik, over hvilke risici der er blevet dækket af litteraturen, hvilket kun var to af de ti predefinerede risikoparametre, som definerede den senere forskning i hele projektet. De to risikoparametre var dog stadig introduceret med bemærkelsesværdige mangler. Et andet udbytte af studiet var oversigten over de specifikke risici for hvert af de målrettede lande i Nordeuropa, da Danmark, Norge, Sverige og Storbritannien blev analyseret individuelt for alle ti risikoparametre. Desuden blev udviklingen i litteratur for hvert land og for Nordeuropa som helhed sammenlignet med udviklingen af vindkraft. Denne multidimensionelle og nye tilgang til gennemførelse af komparative undersøgelser mellem udviklingen af en teknologi og udviklingen af litteratur viste, at tendenser i litteraturen påviser, at samfunds- og vindindustriens opfattelse af risikoparametre skifter, og derfra at udvidelsen af vindkraft til skovområder indfører nye risikobegreber. Den mest alvorlige risiko blev bestemt som ressourcevurderingen af vindforholdene over skove, hvilket kræver en separat undersøgelse af tilgange og potentielle løsninger.

Research Question 1 er blevet besvaret af de to artikler, hvor den første artikel understreger vigtigheden af at definere "skov" som en individuel konfiguration for vindenergi ved at afsløre og undersøge parametre i komparative studier drevet af hypotesestest. Den anden artikel har beskrevet hvilke risici der eksisterer i forbindelse med vindprojekter i skovområder. Dette var afklaret gennem et omfattende litteraturstudie. De to resterende forskningsspørgsmål udvikler sig taksonomisk og undersøger derved risiciene og senere hvordan sådanne risici håndteres.

Den tredje videnskabelige artikel (*Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France*) besvarer Research Question 2 *(How can the risks associated with the siting of wind turbines be limited?)* og søgte at forstå de generelle mekanismer bag social opposition mod onshore projekter. Den anden videnskabelige artikel afslørede, at til trods for at social modstand ikke er nær så hyppig for vindprojekter i skovområder, er årsagerne til at udløse modstand de samme som for andre onshore vindprojekter. Undersøgelsen blev gennemført ved at interviewe interessenter i det franske vindenergimarked, samtidig med at de daglige udfordringer for en vindprojektudvikler blev overvåget og analyseret. Resultaterne af det empiriske studie blev støttet af en litteraturoversigt for at skabe et overblik over årsagerne til social modstand, samt aktiviteter og tiltag for at mindske oppositionen. De konstruerede retningslinjer for, hvordan man øger sandsynligheden for social accept af vindprojektudvikling, er senere anvendt i Research Question 3 for at kortlægge virkningen af social modstand for vindprojekter i skovområder. Denne artikel har derfor ageret grundlag for den senere forskning. Den anden videnskabelige artikel afslørede, at selv om social modstand er en risiko for vindprojektudvikling i skovområder, er den mest alvorlige risiko fortsat estimeringen af vindforhold over trætoppene.

Som et svar på ovenstående fokuserede den fjerde videnskabelige artikel (*From lidar scans to roughness maps for wind resource modeling in forested areas*) på at opsummere, sammenligne og vurdere studier, som har undersøgt tidligere og nuværende tilgange til estimering af vindforhold i og over skove og også en separat metode til gennemførelse af en sådan ressourcevurdering. Den fjerde artikel introducerer The Optimized Roughness Approach (ORA), hvilket er en fremgangsmåde til omdannelse af træhøjder af enten nåletræer eller bredbladede løvfældende træer til ruhedslængder og kort gældende for alle kommercielle softwareprogrammer til vurdering af vindressourcer. ORA er baseret på en kombination af ruhedslængde (Z_0) på $Z_0 = 0.3 \cdot (træhøjde - d)$ og en displacementhøjde (d) på $d = 0.66 * tree\ height$ giver den bedste pasform til nåletrætyper med en gennemsnitlig aboslute fejl på 2.18 %. Dette blev testet mod 34 meteorologiske master ved hjælp af WAsP og WindPRO. Artiklen testede endvidere fire populære online kilder til ruhedskort og fandt ud af, at de alle gav vildledende resultater, hvilket ville kunne ødelægge en ellers fornuftig forretningsplan og endda resultere i alvorlige belastninger på vitale vindmøllekomponenter på grund af en undervurdering af effekten fra skovene. Konklusivt blev tilgangen testet mod forskellige CFD-modeller, der førte til den konklusion, at vindindustrien har brug for data, så som laserskannede målekampagner for at udnytte CFD-modeller i skovområder.

Den femte videnskabelige artikel (*A Socio-Technical Framework for Examining the Consequences of Deforestation and Wind Project Development*) besvarer Research Question 3 (*What is the best approach of managing the risks of siting of wind turbines in Northern European forests?*) ved hjælp af ORA's tilgang til at simulere virkningen af skovrydning fra fire perspektiver; Energiproduktion, Social Opposition, Miljøpåvirkning og Levelized Cost of Energy (LCOE). Den tværfaglige tilgang til denne artikel resulterede i en valideret socio-teknisk model for konsekvenserne af skovrydning i Nordeuropa, når der udvikles nye vindprojekter. Modellen er brugbar for interessenter i vindindustrien for at bestemme, om og potentielt, hvor stort et område der skal fældes. Beslutningen er baseret på alle fire parametre, da det blev afsløret, at indkomsten fra skovrydning ville øge den årlige energiproduktion, men samtidig også øge den sociale modstand, såfremt skoven er naturlig og ikke industriel plantet, forringe miljøpåvirkningen og sænke LCOE. Men uden indtægten fra tømmer vil det økonomiske argument for skovrydning være meget lille og vil ikke blive anbefalet i naturlige skove på grund af den øgede sociale opposition og negativ indvirkning på flora og fauna. Et andet interessant perspektiv er betydningen for lasterne på vindmøllen, da det blev afsløret, at en lysning større end 23 hektarer for en vindmølle med en navhøjde på 115 meter og en rotordiameter på 113 meter ville minimere belastningerne og dermed potentielt udvide vindmøllens levetid, hvilket i dette tilfælde ville medføre en bedre miljøpåvirkning og en lavere LCOE gennem vindmøllens levetid.

Den sjette og sidste videnskabelige artikel (*Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden*) præsenteret i denne afhandling indsamler alle de anvendte studier og resultater og kortlægger Sveriges socio-tekniske begrænsninger i et interaktivt vindatlas ved hjælp af geografiske informationssystemer. Vindatlaset var baseret på interviews med fem overordnede svenske interessentgrupper inden for vindindustrien, dataindsamling af infrastruktur, bygninger og beskyttede områder samt udvikling af et svensk ressourcekort baseret på et omfattende datasæt.

Kortlægningen af vindatlaset gør det muligt at bestemme, hvor i Sverige projekter sandsynligvis vil blive afvist, og hvor de bedste vindressourcer eksisterer. Derudover informerer interessenterne om hvor man skal udvikle vindmølleparker, hvilket revolutionerer de typiske vindatlas, der hovedsageligt har fokuseret på vindressourcer. Det socio-tekniske vindatlas for Sverige viste imidlertid, at de bedste vindressourcer ofte er lokaliseret ved naturbeskyttede områder eller områder med tæt befolkning. Socio-tekniske vindatlas kan afsløre, hvilke skove i et land der er mest hensigtsmæssigt til udvikling af vindprojekter ved at undgå beskyttede naturområder, områder, der opfattes som havende særlig værdi som offentlig ejendom og endelig områder med homogene skovformationer.

Det kan konkluderes, at de tre forskningsspørgsmål er blevet besvaret ved hjælp af en række kvantitative og kvalitative dataindsamlingsmetoder, der sikrer et holistisk perspektiv på de socio-tekniske risici, der skal styres, når vi lokaliserer vindprojekter i de nordeuropæiske skove. Afslutningen af afhandlingen og det industrielle ph.d.-projekt 4135-00033B er, at ændringerne af vindforholdene over skovene kan estimeres ved hjælp af specifikke metoder med højkvalitets data omkring træhøjder og trætyper. Desuden viste afhandlingen, at ressourceevalueringen af et site bør indeholde sociale parametre, da arealanvendelse og social accept også påvirker risikoen for at lykkes med et projekt. Disse risici adskiller sig over landegrænser især for den sociale modstand, når konsekvenserne af skovrydning undersøges.

Contents

List of Figures

List of Tables

List of Equations

1. Introduction

The first chapter frames and introduces the remaining thesis by presenting the subject areas and delimitations of the study. The first part describes the motivation for the research project, both from an academic and industrial point of view. The second part introduces the research questions, including an overview of the papers that were used to answer them. The third and final part introduces the research papers included in this thesis by providing an overview of the content and methodological approach.

1.1 Dissertation Structure

The dissertation is structured through the three research questions and the papers which seek to answer them. The research questions follow the taxonomic steps defined by Bloom (1956), as it is sought to understand and define the risks of wind turbines in Northern European forests, thereafter analyzing these risks to specify why they exist, and finally to manage the risks through the creation of methods and approaches which control and minimize the risks. Table 1 below introduces the relationship between the three research questions and the six journal articles presented in this dissertation.

Table 1 Introduction of applied journal articles

Research Question	Title of Journal Article	Authors	Year	Journal
RQ1: What are the specifications of wind projects in forested areas?	Do onshore and offshore wind farm development patterns differ?	Peter Enevoldsen; Scott Victor Valentine	2016	Energy for Sustainable Development
	Onshore wind energy in Northern European forests: Reviewing the risks.	Peter Enevoldsen	2016	Renewable & Sustainable Energy Reviews
RQ2: How can the risks associated with the siting of wind turbines be limited?	Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France	Peter Enevoldsen; Benjamin K. Sovacool	2016	Renewable & Sustainable Energy Reviews
	From Lidar scans to roughness maps for wind resource modeling in forested areas	Peter Enevoldsen; Ebba Dellwik; Rogier Floors; Neil Davis; Johan Arnqvist	2017	Wind Energy Science
RQ3: What is the best approach to managing	A Socio-Technical Framework for Examining	Peter Enevoldsen	2017	Energy Policy

the risks of wind project development in Northern European forests?	the Consequences of Deforestation: A Case Study of Wind Project Development in Northern Europe			
	Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden	Peter Enevoldsen; Finn Permien	2017	Renewable Energy Focus

The journal articles presented in Table 1 seek to answer the three research questions. For this reason, the journal articles are presented in chapters structured by the research questions. Each chapter is then concluded by a section summing up the important findings, which are presented in the conclusion of this dissertation. The structure of the dissertation is further introduced in Figure 1 below.

Figure 1 Dissertation structure
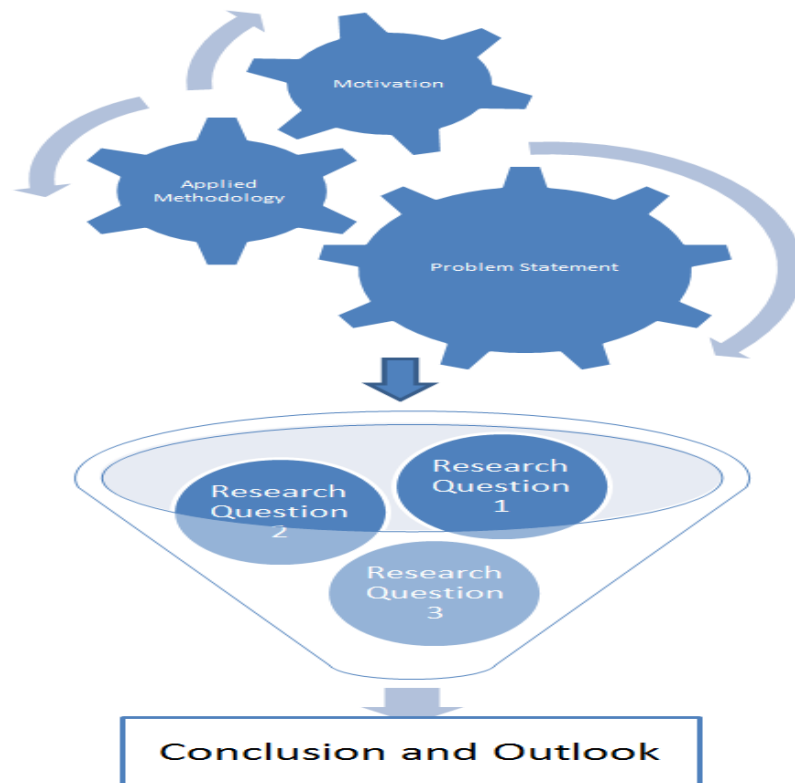
The chapters related to the three research questions cumulate in a section in the overall dissertation conclusion, which summarizes the input from the two respective journal articles, and also includes other arguments from some of the materials published as a part of the industrial PhD project 4135-00033B. The other published materials are part of the industrial PhD project, but have not been included as articles in the thesis, due to their more limited influence on the research questions than the selected six journal articles[1].

---

[1] For an overview of materials published and/or submitted as a part of the Industrial PhD project 4135-00033B, please see Appendix 6.1.

1.2 The Motivation

The following two sections introduce, respectively, the academic and industrial motivation. An industrial PhD's purpose is defined by Innovationsfonden (2017) as being to "*carry out a high quality research project and create results that can lead to commercial gain*" which is why the shared value between academia and business is an important criterion for this dissertation.

1.1.1 The Academic Motivation

Wind power is a topic of considerable study, with more than 2.5 million hits on Google Scholar, and sub-topics of the literature ranging from innovative business models to engineering upgrades of blade attachments. The scientific interest comes as no surprise, as wind, and the resulting kinetic energy, has been harvested by mankind for millennia (Sahin, 2004). This spans from the early Egyptians sailing up the Nile, to the Vikings exploring new lands, to the farmers using the wind to produce food, and ultimately to one of the trademarks of the transition towards a world powered by renewable energy sources. An early successful attempt to convert kinetic energy into electricity was carried out in 1891 by Paul La Cour (Enevoldsen, et al., 2014), and the first horizontal axis three-bladed wind turbine was installed in 1957 followed by the first multi-megawatt wind turbine, which was put into operation in 1978 in Denmark, a wind turbine which is still producing electricity almost 40 years following installation (Folkecenter, 2015). During these 40 years, wind power has transformed into an important electricity source with combined 487 GWs installed in more than 90 countries as of the end of 2016 (IRENA, 2016; Global Wind Energy Council, 2016). The development of installed wind turbines and capacity (MW) is, in particular, due to recent innovations and supportive research and international energy policies (Sovacool & Enevoldsen, 2015). The expansion of wind power is illustrated in the graphs in Figure 2.

Figure 2 Global wind power installations (Global Wind Energy Council, 2016)
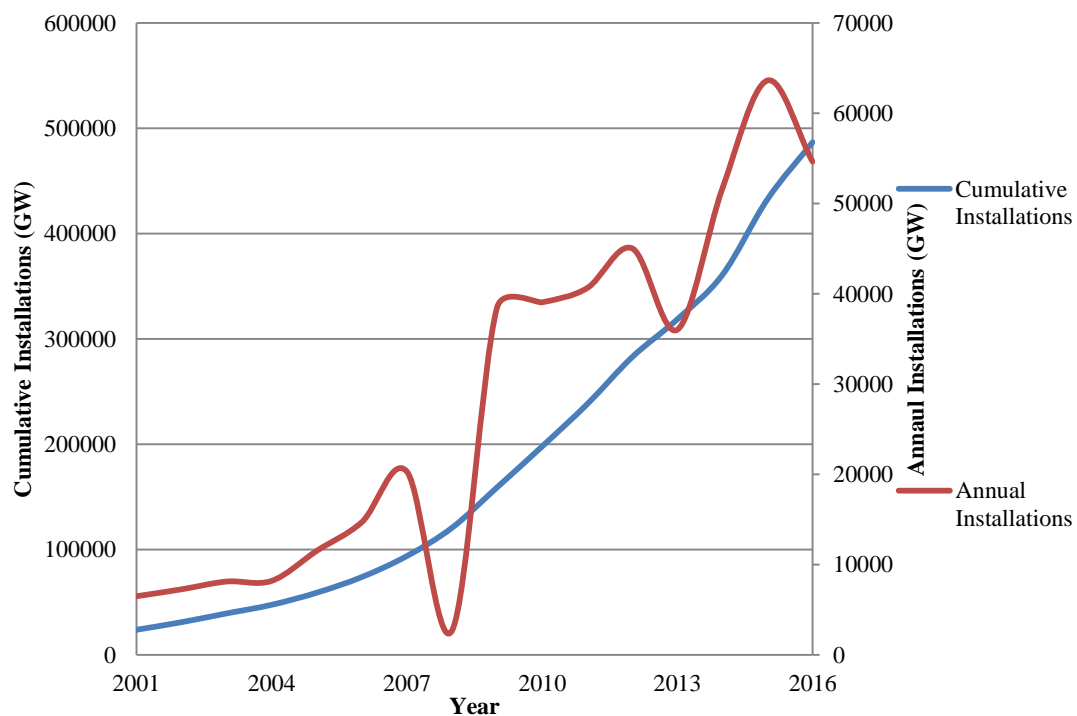
The increasing number of wind farms and expansion to new markets of this global industry has led to wind power employing more than 1 million workers as of 2014 (IRENA, 2015) with the expectation of doubling that number to 2 million by 2030 (Enevoldsen & Valentine, 2016). The early wind turbines were installed in small clusters in Northern Europe funded privately, or as larger farms in California (Gipe, 1991). At this time, the siting of wind turbines was often based on assumptions for the wind conditions, which led to positioning the wind turbines on hilltops and open fields (Wizelius, 2007). However, as the wind turbines grew in popularity, so did the size of the wind farms and the turbines themselves, which required larger investments than small private enterprise and thereby also different locations for the wind turbines. The transition from private to corporate and public investments combined with larger turbines and farms increased social opposition, which is why increasingly developers are recommended to involve local residents in the development and ownership of wind farms (Enevoldsen & Sovacool, 2016). The new locations are, naturally, part of the innovations, which was one of the drivers for the first offshore wind farm in 1991, a configuration of wind farms which has been heavily applied ever since, and especially in the Northern Sea (Bilgili, et al., 2011). However, allowing the installation of larger wind farms, which are still growing, such offshore configurations also come with additional risks for cost overrun and require larger investments per installed MW (Sovacool, et al., 2016).

The Northern European countries targeted in this research, Denmark, Norway, Sweden, and the UK, have all had their individual development of wind power – with Denmark being a pioneer, the UK the country with most installed offshore wind turbines, Sweden with a rapid increase in the installed capacity during the past 10 years and, finally, Norway, with a great potential but still lacking a wide-scale breakthrough (EWEA, 2016). The development of installed capacity (MW) for each country is illustrated in the graph in Figure 3.

Figure 3 Wind Power installations for the targeted northern European countries (Global Wind Energy Council, 2016)
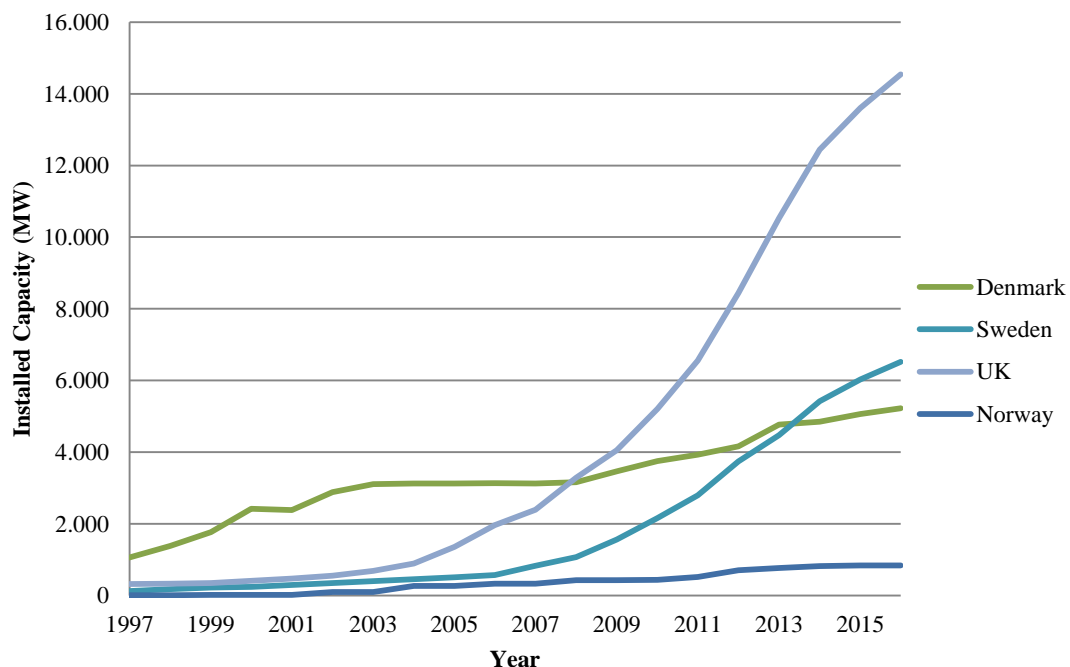
The graphs in Figure 3 clearly show that Denmark had already had a large number of wind turbines installed two decades ago, while offshore plants have resulted in the explosive expansion of wind

power in the UK and favorable energy policies have helped the Swedish installed capacity rise to a level above the situation in the green state of Denmark. These developments have been compared to the annual global growth (%) in installed wind power capacity. As mentioned, the Norwegian boom is potentially anticipated in the future, and has therefore not been considered in Figure 4.

Figure 4 Global versus Northern European wind power growth
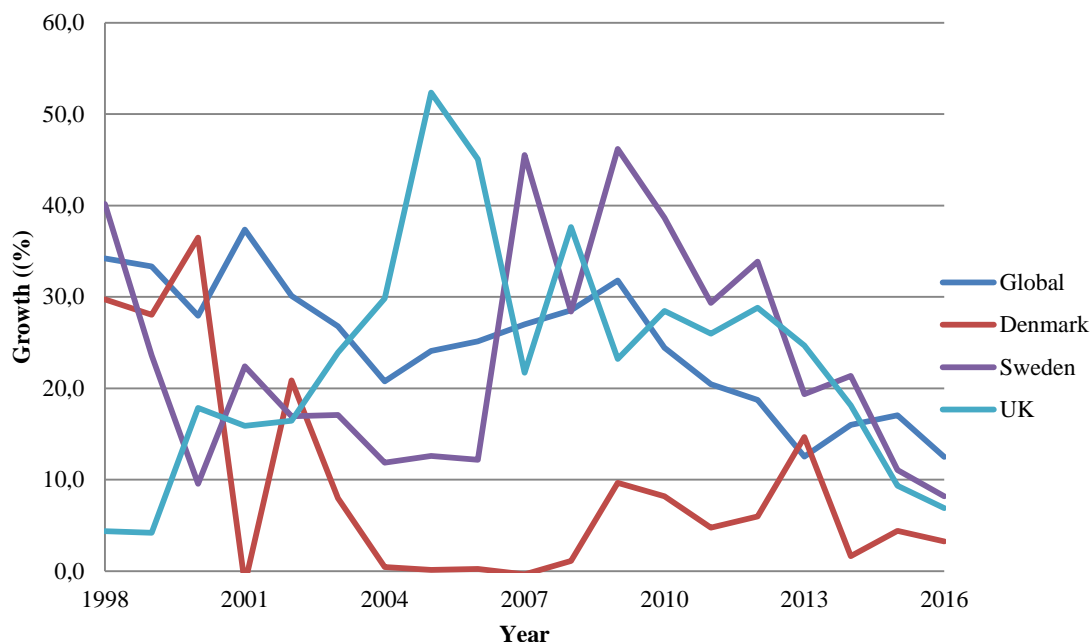
Figure 4 shows the development for Sweden and the UK has been greater than the global average for the past five years. The great expansion of wind power in Denmark, Sweden, and the UK has cumulated in increasing costs for acquiring land onshore, and also increasing social and political opposition. The above, in combination with the challenges of the offshore configuration and the growing size of wind turbines, has led to a new location being taken into consideration for wind turbine deployment, the forests.

Deploying wind turbines in forested areas in Denmark, Sweden, the UK, and potentially also Norway, comes as no surprise since these countries are heavily covered by forests, as presented in Table 2.

Table 2 Forest coverage in the targeted countries (Enevoldsen, 2016)

Country	Area of country covered by forest (%)	Coverage of dominating tree types (%)
Denmark	13.5%	Abies alba and Picea abies 40.4%
		Various deciduous tree types 39.5%
Norway	38%	Picea abies 47%
		Pinus sylvestris 33%
Sweden	66%	Picea abies 42%
		Pinus sylvestris 39%
The UK	12%	Picea sitchensis 29%
		Pinus sylvestris 17%
		Various deciduous tree types 40.2%

The expansion of wind power in forested areas in the targeted countries is supported by wind conditions which favor the performance of the wind turbines (Troen & Petersen, 1989). Furthermore, all of the countries have forestry as an industry, which could potentially decrease the initial barriers for the introduction of forests as a location for wind farms. However, the precautions and planning for wind projects in forested areas are expected to differ from regular onshore projects, and few, if any, studies have adequately explored the risks relating to wind farm development in European forests (Binz, et al., 2012). That being said, a consensus exists between researchers when defining the estimation of wind conditions as the gravest risks for wind project development in forested areas (Bergström, et al., 2013), even despite decades of research having provided answers for the wind flows above various forest canopies (Baldocchi, 1988; Hicks, et al., 1975; Jarvis, et al., 1976; Raupach & Thom, 1981; Arnqvist, et al., 2015). Nevertheless, the majority of the studies dates back more than two decades, where the focus was on surface-layer theory and turbulence near the canopy, and not directly on the impact on wind turbine performance. Nonetheless, Wenzel, et al. (1997) determined how forests impact wind flows 100 meters above the canopy, which was followed up more than a decade ago when Dellwik, et al. (2006) concluded that the modelling of wind flows in forests could be applied as a decent output, providing estimating in non-complex terrains and homogenous forests. The expansion of installed wind power capacity has increased dramatically since then, forcing the wind turbines to be located in heterogeneous forests with different tree types, heights and clearings, which complicates the estimations of the impact from the forest and thereby the behavior of the wind at the hub height of multi-megawatt wind turbines (Dellwik, et al., 2014; Boudreault, et al., 2017). At the same time, the increasing size of the wind turbine, forces the wind industry to estimate changes in wind conditions in the vertical boundary layer, which will change significantly over forest canopies (Arnqvist, 2013).

In addition, the literature and the industry had not provided an overview of the content of other risks such as social and political opposition and miscalculated performance, which have been extensively studied for onshore wind power in general. In conclusion, the new trend of deploying wind turbines in forested areas is expected to involve different risks from that experienced and discussed in academia, which is why an examination and understanding of these risks are required.

1.1.2 The Industrial Motivation

Siemens Wind Power A/S (as of April 1, 2017 Siemens Gamesa Renewable Energy) has deployed more than a thousand wind turbines in the UK, Norway, Sweden and Denmark, and has therefore also encountered the challenges of locating wind turbines in forested areas. Having based the resource assessments on the know-how and data available in the industry, the company rapidly discovered that some of the wind turbines performed differently to expectation. Such unexpected behaviors were linked to the unpredictability of the wind conditions in and above the forest canopies, where the annual energy production and the errors were different from the expected scenario[2]. The easy solution for such an issue would be to deforest the entire area before constructing the project. That was, nevertheless, never an option, as one of the key motivators of Siemens Gamesa Renewable Energy is to strengthen the environment and enforce the transition towards a society based on 100% renewables.

Besides the obvious challenge of developing a guideline on how to estimate the wind conditions, the task was to find a guideline which could easily be implemented in the daily work of the siting engineers, who use standardized software packages, which have been accepted as the norm by the

---

[2] Internal analyses have been carried out to estimate the exact impact of the forest. These numbers have, however, not been included in this thesis due to reasons of confidentiality. Anonymized graphs will be introduced at the oral defense.

majority of the stakeholders in the wind industry. These software packages are briefly introduced below:

WindPRO: *"a module-based software package suited for project design and planning of both single WTGs and large wind farms."*

WAsP: *"the industry-standard for wind resource assessment, siting and energy yield calculation for wind turbines and wind farms."*

WindSim: *"a powerful, world-class software based on computational fluid dynamics (CFD) that combines advanced numeric processing with compelling 3D visualization."*

In addition to the external software packages, the intention was to provide models which would support the internal software and models. Another interesting challenge was to include and formulate the potential social opposition which could be expected for wind project development in forested areas, which was why a part of the research project focused on this issue. This was considered a novel study area from the usual concern of siting engineers in Siemens Gamesa Renewable Energy, which is why it was sought to implement such tools as those used in the software packages used on a daily basis. Summarizing the industrial motivation leads to the formulation of the overall industrial challenges. These challenges differ slightly from those revealed from an academic perspective:

Industrial Challenge 1: *How should Siemens Gamesa Renewable Energy estimate the wind conditions above forest canopies?*

Industrial Challenge 2: *What are the social consequences of siting wind turbines in forested areas?*

Industrial Challenge 3: *How can the risks associated with the siting of wind turbines in forested areas be limited and incorporated in the software packages used by Siemens Gamesa Renewable Energy?*

Finally, how to formulate and disseminate the research outputs through large and well-known industrial conferences has been explored, in order to brand the new focus and know-how of the company. For this reason, the majority of the papers have formed the foundation for oral presentations with a particular focus on industrial needs and influence. This has secured a strong transition between the academic findings and practical and usable knowledge in the company.

1.3 The Research Questions

It was sought to formulate research questions which would frame the entire research project and dissertation, and, at the same time, ensure knowledge distribution by understanding, discussing, and improving the academic knowledgebase on risks associated with wind turbines in forested areas. Based on the academic and industrial motivation, the following main question was formulated to frame the research:

What design principles limit the risks of siting wind turbines in Northern European forests?

The main research question seeks to find solutions to the expected risks of siting wind turbines in forested areas in Northern Europe. However, in order to answer such a question, a number of related research questions needs to be explored:

Research Question 1: *What are the specifications of wind projects in forested areas?*

Included in this research question is a firm descriptive definition of what defines a wind project in a forest, in order to distinguish them from other wind projects. The aim is to reveal the specific patterns for wind in forested areas from a socio-technical perspective. Furthermore, it was considered important to establish an overview of when such risks exist in the lifecycle of a wind project, and the interconnection between the risks

Research Question 2: *How can the risks associated with the siting of wind turbines be limited?*

The second research question was established to ensure that the expected risks from the initial literature study and the preconceptions from the company cover all, and the most appropriate, risks. This research question has a specific focus on a risk with which academia and the industry is familiar, namely the uncertainty of estimating wind conditions above Northern European forest canopies. The social opposition of onshore wind power is furthermore analyzed, in order to later understand the interdisciplinary risks associated with wind power in forested areas.

Research Question 3: *What is the best approach to managing the risks of wind project development in Northern European forests?*

The third research question introduces methods on how to deal with risks associated with wind project development in forested areas, in order to manage all risks and ensure a continuous development of onshore wind farms in Northern Europe.

In Table 3 below, the research questions have been placed in relation to the industrial challenges.

Table 3 Relationship between research questions and industrial challenges

		Research Questions		
		RQ1: What are the specifications of wind projects in forested areas?	**RQ2:** How can the risks associated with the siting of wind turbines be limited?	**RQ3:** What is the best approach to managing the risks of wind project development in Northern European forests?
Industrial Challenges	**IC1:** How should SWP estimate the wind conditions above forest canopies?		X	X
	IC2: What are the socio-political consequences of siting wind turbines in forested areas?	X	X	
	IC3: How can the risks associated with the siting of wind turbines in forested areas be limited and incorporated in the software packages used by SWP?		X	X

As introduced in Table 3, there is a clear correlation between the industrial challenges and the research questions, which were based on the academic motivation. The research questions will be used to structure the thesis by introducing publications answering those questions.

1.4   Applied Methodology

This section introduces and outlines the research design and methodological approaches applied in the studies presented in this dissertation. This is performed by introducing the overall research philosophy and design. Thereafter, an introduction follows to all of the studies, as the approaches for each of the six papers included in this dissertation are presented and discussed.

1.1.3   Research Philosophy

Having defined the problem formulation and research question, the next step is to devise a research strategy (Blaikie, 2010). Such a strategy or logic of inquiry has to be carried out within certain boundaries, which are related to the overall research philosophy. Academics seem to disagree on what defines such boundaries, yet Guba (1990) suggests defining research paradigms and logic of inquiries by answering an ontological, epistemological and methodological question. Blaikie (2010) further argues that research paradigms can be applied differently, as different research strategies can be applied within the same research project.

At first glance, the engineering problem's formulation and research questions indicate a taxonomic step-by-step approach defining the nature of the problem, examining it, and finally implementing approaches to overcome the problem. This would suggest the usage of a classic positivism paradigm system by acknowledging a true and objective nature and defining a conjunction between the studied objects (Blaikie, 2010). Such an approach has partly been used in this dissertation following results relying on the experience of testing the relationship between objects related to the development of methods for estimating wind conditions above forest canopies. However, no forest is alike, and the resource assessment is not the only risk category that has been studied in this research. The social aspects of the risks involved with deploying wind farms in forested areas, and a weighting of such risks against the impact on the wind resources of, for example, limiting deforestation, calls for interdisciplinary and understanding of a nature which cannot be perceived as an absolute unity (Creswell, 2009).

The apparent need for mixed methods to examine the interdisciplinary context of risks associated with wind project development could indicate the usage of a pragmatic paradigm as defined by Creswell (2009). Pragmatism, as defined by Howe (1988), endorses the usage of mixed methods as multiple methods and data collection approaches are required to fully understand a research problem, which thereby also includes subjective and objective knowledge. However, pragmatism has also been criticized as the researcher can be driven by expected outcomes, and furthermore that the unstructured involvement of mixed methods and reasoning strategies could potentially pollute results due to the subjective involvement of the researcher (Tashakkori & Teddlie, 1998).

Instead, post-positivism, as defined by Guba (1990), which, in contrast to Creswell's (2009) definition of post-positivism allows the usage of qualitative measures in the falsification of objects, has been used to define the research studies conducted in this dissertation. The usage of post-positivism has been described by answering the ontological, epistemological, and methodological questions, as defined by Guba (1990). At an ontological level, it is sought to find the nature of reality, by investigating the existing objects (Guba, 1990), albeit with the difference from pure positivism that such a reality cannot be fully revealed, although it should be the goal of the study. This approach is defined as critical realism, which, translated to the practical work in this research, equates to an examination of all possible objects defining the true nature, including detailed literature reviews, carefully planned interviews and wind data collections from validated sources. Answering the

epistemological question provides a definition of the relationship between the researcher and the nature of reality which is studied. Again, the main target is objectivity, yet modified in the sense that it is acknowledged that the researcher and used data have a preunderstood impact on the results. In order to overcome such a bias, it has been sought to include several perspectives on the same problems in the presented journal articles. Therefore, a single research question has not been considered to be confirmed using only one approach, and has sequentially been challenged using the input from various data collections. Finally, the methodological question asks how a researcher can reveal what is to be known in order to define the nature of reality. Critical multiplism, meaning a triangulation of data and research inputs, is applied to ensure the validity of the outputs. The modified experimental approach allows the usage of qualitative measures in the falsification of hypotheses on the nature of reality. Guba (1990) further describes that the falsification process carried out using mixed methods, can equally serve as a discovery for new findings in a modification of post-positivism, which has been the case in several of the presented journal articles.

1.1.4 Mixed Methods: A Requirement for performing Socio-Technical Studies

The approach applied in this research is inspired by the recommendation from Sovacool (2014) on including social science when examining engineering challenges. For this reason, the entirety of this research aims at triangulating and formulating holistic patterns by the usage of quantitative and qualitative measures. Such an approach is considered necessary to examine:*"What design principles limit the risks of siting wind turbines in Northern European forests?",* as several approaches and perspectives are required to study the interdisciplinary nature of this topic. Following the defined research paradigm, a well-structured approach can allow the usage of mixed methods.

Mixed methods apply multiple methods and potentially also logic reasonings to reveal the truth. The reasonings applied in this dissertation are: 1) the inductive reasoning to answer the *What* questions by searching for patterns in empirically obtained data, 2) the deductive reasoning, when answering *Why* questions in relation to explanation of experienced events (Creswell, 2009), and 3) predominantly, the retroductive reasoning used to discover the underlying mechanisms, which thereby seeks to determine the nature of reality for the purpose of examination, in order to find a logic in the discovery. The retroductive reasoning allows the researcher to falsify a hypothesis multiple times whenever no discoveries are made, which is in connecting thread with the modified description of post-positivism (Blaikie, 2010).

The mixed-methods approach using both qualitative and quantitative data collections is adopted to provide a complete answer to the research questions (Creswell, 2009), which is in accordance with the chosen research paradigm. Mixed methods allows both pre-determined and/or emergent approaches, where the first approach has been applied to define and conduct experiments, while emergent approaches have included theory inductively to explain unexpected outcomes. In order to avoid the subjective bias of using mixed methods in an unstructured manner, the search for contextual patterns is facilitated by introducing quantitative measures and literature in order to understand the nature of the problems, and conduct experiments, which thereafter are questioned and further discovered using qualitative measures. This approach is carried out to ensure that each data collection and interpretation methods complements the other, while being an integral part of securing the validity of the outputs (Guba & Lincoln, 1994). Mixed methods further allows the researcher to apply different research designs (Creswell, 2009), the practical usage of which are elaborated in the following.

1.1.5   Research Designs

The comparative multiple case studies carried out in the dissertation seek to generalize the performance and impact of wind turbine in forested areas. One advantage of this research design is that while generic patterns are the target of the research, individual information can also be derived from each case included, which can subsequently be compared to establish informative literature. For example, the aim of Research Question 1 is to define the specifications for wind projects located in forested areas, which is why multiple cases needed to be involved, in order to separate such projects from the remaining configurations (Yin, 2003), which according to Baxter & Jack (2008) also strengthens the validity of the research outputs. Eisenhardt (1989) recommends discussing the outputs of case studies with the current literature, which is in accordance with the post-positivism research paradigm.

For example, literature was used to explain the patterns discovered in the first journal article of the dissertation, while the existing literature was challenged in the fifth journal article over the findings from the single case study. A single case study allows the researcher to study specific details (Eisenhardt, 1989), which was required in the determination of the consequences of deforestation.

The literature study applied in the second journal article seeks to reveal and establish an overview of the present state of academic contributions to risks associated with wind turbines in forested areas in Northern Europe. Literature reviews are carried out in all of the journal articles in this dissertation to critically analyze prior studies; however, this article examined the literature following a set of principles, which revealed the trends in literature. This approach was conducted using a structured search, which ensured the filtering of non-relevant materials (Sovacool & Brossmann, 2010). The combination of a literature review and a quantitative triangulation resulted in statistical trends in accordance with the research paradigm.

The third journal article applied a research design similar to the one in the first article. Two interconnected methods were used, the semi-structured research interviews, and a targeted literature review. The single case study following the French wind project developer ensured insight in details about social opposition, which were validated and generalized using literature. The qualitative data served both as the incentive for the research, and also as potential solution to the challenge of social opposition. This approach was only considered viable, due to the interconnected research design where empirical data were triangulated using existing research.

The fourth journal article presents a classical experiment of testing different inputs by manipulating the reality and introduces a set of objects, the impacts of which are compared to the reality of nature. Performing such a study allows the researcher to objectively explore different parameters, and thereby define a best approach. The overall deductive reasoning in this article defined variables derived from existing literature, but also questioned using such literature, which is a vital part of ensuring validity in case studies. That approach is an example of how an overall retroductive mindset has been applied in all the conducted studies.

The fifth journal article is an example of a socio-technical study as described by Sovacool (2014), as the consequences of deforestation are covered by a holistic approach examining objective measures such as changes in wind speed and the environmental impact of deforestation. These classic engineering studies were compared and measured against the impact on social opposition, and finally a reflection on how the consequences could impact upon the levelized cost of energy for a wind project in a forest. The data collection was based on mixed methods, in order to establish a socio-

technical framework which can be applied as an engineering tool, albeit only if including qualitative analyses.

The sixth and final journal article applies the same methodology as the fifth, as a wind atlas was constructed and modified using layers of hard and soft restrictions, where the latter was defined by Swedish stakeholders. The opinion and impact of the Swedish stakeholders were revealed following a qualitative data collection from more than 40 semi-structured interviews that followed an interview guide and principles as defined by Brymann & Bell (2007) in order to avoid leading questions and, at the same time, gather the valuable knowledge of the respondents. After having defined the stakeholder groups, a snowball technique was carried out to screen and reveal further potential stakeholders, as applied by Enevoldsen, et al. (2014). Thereafter, all respondents were treated equally and areas which could increase opposition were considered restrictive for wind project development.

Table 4 summarizes the research design for each of the six journal articles presented in this dissertation. The in-depth description of the applied research designs are presented in each of the journal articles.

Table 4 Introducing the applied research designs

Research Question	Article	Subject to be studied	Data Collection	Research Analysis
What are the specifications of wind projects in forested areas?	1	The difference in performances between wind farms located onshore, offshore, and in forests.	• Peer-reviewed literature • Market reports • Performance data from 44 operating wind farms	The empirical data was studied using a comparative statistical approach, which was based on five preconceptions defined by peer-reviewed literature and market reports.
	2	The current state of literature covering risks associated with wind farms in forested areas in Northern Europe.	• Peer-reviewed literature • Market reports	The findings in the literature review were structured by a pre-defined risk framework, and later compared to trends in wind power development in each of the targeted countries.
How can the risks associated with the siting of wind turbines be limited?	3	The reasons for social opposition of onshore wind power, and guidelines for limiting such opposition.	• Peer-reviewed literature • Semi-structured interviews	The empirical data was collected through interviews with stakeholders during the project development. Hereafter literature was used to structure and validate the empirical input.
	4	The best approach for minimizing the risks of misestimating	• Peer-reviewed literature • Wind data from Seven	A test was carried out using a cross-case analysis to compare estimation methods. A

		wind conditions above coniferous forests in Northern Europe.	Meteorological Masts • Online available roughness maps	statistical regression analysis revealed the best approach.
What is the best approach to managing the risks of wind project development in Northern European forests?	5	The multi-level consequences of deforestation in Northern Europe	• Peer-reviewed literature • Wind data from seven Meteorological Masts • Deforestation emission tool	The complexity of involving quantitative and qualitative measures in a framework based on interdisciplinary inputs was solved by establishing a framework, which was tested repeatedly applying a retroductive reasoning
	6	The creation of the world's first country-based socio-technical wind atlas revealing potential areas for wind project development in Sweden	• Peer-reviewed literature • More than 500 physical measurement devices • A wind atlas • 40 semi-structured interviews with eight stakeholder groups • Open street map data	The interdisciplinary nature of this study required a mixed-methods approach, where qualitative outputs were weighted against quantitative measures and literature. The combined output was mapped using GIS-software.

1.5 References

Arnqvist, J., 2013. *Mean Wind and Turbulence Conditions over Forests ,* Uppsala: Department of Earth Sciences Licentiate Thesis.

Arnqvist, J., Segalini, A., Dellwik, E. & Bergström, H., 2015. Wind Statistics from a Forested Landscape. *Boundary-Layer Meteorology,* Volume 156, p. 53–71.

Baldocchi, D. &. M. T., 1988. Turbulence structure in a deciduous forest. *Boundary-Layer Meteorol ,* Volume 43, p. 345–364.

Baxter, P. & Jack, S., 2008. Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers.. *The Qualitative Report,* 13(4), pp. 544-556..

Bergström, H. et al., 2013. *Wind Power in forests,* s.l.: Elforsk.

Bilgili, M., Yasar, A. & Simsek, E., 2011. Offshore wind farm development in Europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews,* Volume 15, pp. 905-915.

Binz, R., Sedano, R., Furey, D. & Mullen, D., 2012. *PRACTICING RISK-AWARE ELECTRICITY REGULATION: What Every State Regulator Needs to Know,* Boston: Ceres.

Blaikie, N., 2010. *Designing Social Research.* 2nd ed. s.l.:Wiley.

Bloom, B., 1956. Taxonomy of Educational Objectives.

Boudreault, L.-É., Dupont, S., Bechmann, A. & Dellwik, E., 2017. How Forest Inhomogeneities Affect the Edge Flow. *Boundary-Layer Meteorology,* Volume 162, p. 375–400.

Brymann, A. & Bell, E., 2007. *Business Research Methods.* 2nd ed. Oxford: Oxford University Press..

Creswell, J., 2009. *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches.* Los Angeles: Sage.

Dellwik, E., Bingöl, F. & Mann, J., 2014. Flow distortion at a dense forest edge. *Quarterly Journal of the Royal Meteorological Society,* Volume 140, pp. 676 - 686.

Dellwik, E., Jensen, N. & Landberg, L., 2006. Wasp in the forest.. *Wind Energy.*

Eisenhardt, K. M., 1989. Building Theories from Case Study Research.. *The Academy of Management Review,* 14(4), pp. 532-550.

Enevoldsen, P. & Sovacool, B. K., 2016. Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France. *Renewable & Sustainable Energy Reviews,* pp. 178-184.

Enevoldsen, P., Sovacool, B. K. & Tambo, T., 2014. Collaborate, involve, or defend? A critical stakeholder assessment and strategy for the Danish hydrogen electrolysis industry. *International Journal of Hydrogen Energy,* Volume 39, p. 20879–20887.

Enevoldsen, P., Sovacool, B. & Tambo, T., 2014. Collaborate, Involve, or Defend? A Critical Stakeholder Assessment and Strategy for the Danish Hydrogen Electrolysis Industry. *International Journal of Hydrogen Energy,* 39(36), p. 20879–20887.

Enevoldsen, P. & Valentine, S. V. .., 2016. Do onshore and offshore wind farm development patterns differ?. *Energy for Sustainable Development,* Volume 35, pp. 41-51.

EWEA, 2016. *Wind in power 2015 European statistics,* Brussels: EWEA.

Folkecenter, 2015. *www.folkecenter.dk.* [Online]
Available at: http://www.folkecenter.dk/dk/news/int/tvindmoellen-40-aar/
[Accessed 22 April 2017].

Global Wind Energy Council, 2016. *www.gwec.net.* [Online]
Available at: http:///wp-content/uploads/vip/Global_Cumulative_Installed_Wind_Capacity_2000-2015.jpg
[Accessed 2 May 2017].

Guba, E., 1990. The paradigm dialog.

Guba, E., 1990. *The Paradigm Dialog.* Thousand Oaks: Sage.

Guba, S. E. & Lincoln, S. Y., 1994. Competing Paradigms in Qualitative Research. In: *Handbook of Qualitative Research.* Thousand Oaks: Sage, pp. 105-117.

Hicks, B. B., Hyson, P. & Moore, C. J., 1975. A Study of Eddy Fluxes Over a Forest. *Journal of Applied Meteorology ,* Volume 14.

Howe, K., 1988. Against the quantitative-qualitative incompatibility thesis or dogmas die hard. *Educational Research,* Volume 17, p. 10–16.

Innovationsfonden, 2017. *www.innovationsfonden.dk.* [Online]
Available at: https://innovationsfonden.dk/en/application/erhvervsphd
[Accessed 23 March 2017].

Jarvis, P. G., James, G. B. & Landsberg, J. J., 1976. Coniferous Forest. *Vegetation and the Atmosphere,* Volume 2, pp. 171-240.

Raupach, M. & Thom, A., 1981. Turbulence in and above Plant Canopies.. *Annual Review of Fluid Mechanics ,* Volume 13, pp. 97-129.

Sahin, A. D., 2004. Progress and recent trends in wind energy. *Progress in ENergy and Combustion Science,* Volume 30, pp. 501-543.

Sovacool, B., 2014. Energy Studies Need Social Science. *Nature,* Volume 511, pp. 529-530.

Sovacool, B. & Enevoldsen, P., 2015. One style to build them all: Corporate culture and innovation in the offshore wind industry. *Energy Policy,* 11(85), pp. 402-415.

Sovacool, B., Enevoldsen, P., Koch, C. & Barthelmie, R. J., 2016. Cost performance and risk in the construction of offshore and onshore wind farms.. *Wind Energy.*

Sovacool, B. K. & Brossmann, B., 2010. Symbolic convergence and the hydrogen economy. *Energy Policy,* Volume 38, p. 1999–2012.

Tashakkori, A. & Teddlie, C., 1998. *Mixed Methodology: Combining Qualitative and Quantitative Approaches..* London: Sage.

Troen, I. & Petersen, E., 1989. *European Wind Atlas.* Roskilde: Risø National Laboratory .

Wenzel, A., Kalthoff, N. & Horlacher, V., 1997 . On the profiles of wind velocity in the roughness sublayer above a coniferous forest. *Boundary Layer Meteorology,* Volume 84, p. 219–230.

Wizelius, T., 2007. *Developing Wind Power Projects.* 1 ed. London: Earthscan.

Yin, R. K., 2003. *Case study research: Design and methods..* 2nd ed. Thousand Oaks: Sage.

2 What are the specifications of wind projects in forested areas?

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

1. *Do onshore and offshore wind farm development patterns differ? / Enevoldsen, Peter; Valentine, Scott Victor. / Energy for Sustainable Development, Vol. 35, Nr. December 2016, 2016, s. 41-51. / DOI: 10.1016/j.esd.2016.10.002*

2. *Onshore wind energy in Northern European forests: Reviewing the risks. / Enevoldsen, Peter. / Renewable & Sustainable Energy Reviews, Vol. 60, 2016, s. 1251–1262. / DOI: 10.1016/j.rser.2016.02.027*

The two journal articles aim at revealing the specifications and patterns of a wind project in a forested area. The first article is examining the performance of wind farms located onshore without forest, offshore, and finally onshore with forestry. The second article is determining and examining the risks associated with wind projects in forested areas.

2.1 Do onshore and offshore wind farm development patterns differ?

The first journal paper included in this dissertation examines and presents the performance of more than 1,000 operating wind turbines located offshore, onshore, and onshore in forested areas. The purpose of the study was to analyze the potential differences between wind farm configurations, based on investigations between the power output and socio-technical parameters making use of data from 44 wind farms, including 11 offshore wind farms, 19 onshore wind farms located in farmland and 14 wind farms located in forested areas with a total capacity of 1,190 MW installed actual wind farms to test four hypotheses based on preconceptions identified in a literature review. Testing the validity of these preconceptions is important because if policymakers are to design policy to facilitate specific development patterns in a given nation, they need to be clear on what is working in the market. A remarkable finding associated with this study is that onshore wind turbines that are located in forested areas might be capable of matching the power production of offshore wind farms without incurring the additional costs associated with offshore projects. This paper has been introduced in the dissertation, in order to provide an understanding of some of the generic differences between wind farms located in forested areas and the well-known configurations of onshore without forest and offshore.

2.1.1 Introduction

The sight of a wind turbine on the horizon has come to encapsulate what many perceive to be the initial stages of a transition to low carbon energy. There is good reason for this. Global wind power potential is enormous. In a 2005 study, Archer and Jacobson (2005) determined that capturing only 20% of technical potential using existing turbine technology "could satisfy 100% of the world's energy demand for all purposes (6995–10177 Mtoe) and over seven times the world's electricity needs (1.6–1.8 TW)". Another team of researchers from Harvard University and the VTT Technical Research Center in Finland estimated in 2009 that "a network of land-based 2.5-megawatt (MW) turbines restricted to non-forested, ice-free, nonurban areas operating at as little as 20% of their rated

capacity could supply more than 40 times current worldwide consumption of electricity" and more than "5 times total global use of energy in all forms" (Lu et al., 2009).

During the past two decades, companies worldwide have begun to harness this untapped potential. Installed wind energy capacity has increased from less than 8,000 MW in 1997 to more than 432,000 MW by the end of 2015 (IRENA, 2016). Moreover, the sector has established itself as a major source of new employment, topping 1 million workers in the sector for the first time in 2014 (IRENA, 2015) with an expected doubling to 2 million by 2030. Indeed, on a kilowatt hour basis, it has been estimated that wind power produces 55% more jobs than coal-fired power and natural gas-fired power; and 21% more jobs than nuclear power (WRI, 2010).

To date, the majority of wind power projects have been constructed onshore. As of the end of 2015, of the 432,000 MW of installed wind power capacity, 420,000 MW exists onshore (IRENA, 2016). The first onshore multi-megawatt wind turbines were installed in 1978 in Denmark (Gipe, 1995b) and were primarily installed in farmlands – which permitted joint use projects that lower costs - and in close proximity the sea, to take advantage of stronger coastal wind profiles (Manwell, 2009; Troen and Petersen, 1989). However, as wind power projects have grown in concentration, so has social opposition with not-in-my-backyard (NIMBY) sentiments clearly on the rise (Valentine, 2011).

In response, many nations are adjusting policies to encourage offshore wind power development (Valentine, 2014). For almost a decade, planners have seen great potential in offshore wind energy and lauded such developments as a way to avoid both the high cost of acquiring onshore tracts of land and social opposition to further onshore development (Ladenburg, 2009). Recent innovations in offshore foundations has made it possible to deploy wind turbines in deeper waters, enhancing global offshore wind potential (Adelaja et al., 2012). Consequently, offshore wind power capacity is on the rise, reaching 12,000 MW by the end of 2015 (IRENA, 2016). Offshore capacity is expected to increase rapidly in the coming years, especially in Europe (Young, 2015).

The pace of offshore development is highly contingent on the economics of any given offshore wind power project. Some research suggests that offshore wind farms exhibit cost advantages through less costly wind turbine materials because towers can be constructed at lower heights. However, most studies counter that offshore wind farms are more expensive to construct and maintain, due to the demand for larger fortified foundation structures, submarine cables and special vessels for transportation and installation (Bilgili et al., 2011). The general consensus is that offshore wind farms are still more costly than onshore options for generating energy. Yet, as perhaps a testament to market sentiments that offshore wind power projects present greater appeal due to lower risk of social opposition, one influential market report predicting low, central and high scenarios for installed wind energy in the EU in 2020, contends that offshore wind power will exhibit higher annual growth (%) than onshore wind power (EWEA, 2014).

The difficulties of earmarking suitable tracts of open land for onshore wind farms and the depressed rates of return for offshore wind projects has encouraged some wind project developers to search for non-traditional sites onshore. The increased tower heights of multi-megawatt wind turbines (Leung & Yang, 2012; Manwell, et al., 2009) has made it possible to deploy wind farms in forested areas where land acquisition is cheaper and investment risks are lower because social opposition is expected to be lower due to increased distance to neighbors (Enevoldsen and Sovacool, 2016).

The reason why onshore wind farm development in forests merits special attention is because siting profiles differ markedly. The land use spectra for wind turbines in forested areas are different (Perks,

2010; Dai, et al., 2015). Moreover, altered surface patterns cause shifts in wind profiles (Arnqvist, 2013; Dellwik, et al., 2014), increasing turbulence and wind shear. Yet, from the existing literature there are indications that wind turbines deployed in forested areas are more likely to produce less electricity and have a shorter life span than other onshore wind farms (Enevoldsen, 2016). Nevertheless, studying onshore wind farms in forested areas is important because in some of the countries with high amounts of installed wind capacity, wind farms are increasingly being deployed in areas of managed forests, where owners are looking for extra income on land that cannot be used for farming (Enevoldsen, 2016).

Amidst this market flux with developments occurring within traditional onshore locations, in forested areas and in offshore sites, it merits investigating whether there any differences in development patterns. When developers are building wind farms offshore or onshore, are there notable characteristics that differentiate these projects? If so, what does this tell us about the nature of wind power development patterns? There are a number of preconceived notions. For example, a prominent assumption is that offshore wind farms will generate more energy per turbine than onshore farms. But does this assumption hold true when one compares data from actual wind power developments? Testing the validity of these preconceptions is important because if policymakers are to design policy to support specific development strategies in a given nation, they need to be clear on what is working in the market.

This study makes use of data from actual wind farms to test four hypotheses based on preconceptions arising from a literature review. The data used for this study is based on 44 different wind farms, including 11 offshore wind farms with a total installed capacity of 3589 MW, 19 onshore wind farms located in farmland with a total installed capacity of 1395 MW and 14 wind farms located in forested areas with a total capacity of 1190 MW installed.

2.1.2 Research Design, Hypotheses and Methodology

Research Design

The methodology adopted for this study centers around access to data from operational wind farms. For this reason alone, this study represents an uncommon opportunity to gain insight into what is actually transpiring in the wind power market. As mentioned above, the data used in this study comes from 44 different wind farms: 11 offshore wind farms, 19 onshore wind farms located in farmland and 14 wind farms located in forested areas.

The offshore wind projects are mainly located in the European region, which is due to the fact that Europe is the continent with the most installed offshore wind power (GWEC, 2016). The onshore projects are spread all over the world and the wind projects in forested areas are mainly located in Northern Europe, as some of the leading countries in wind energy development has been forced to locate newer wind projects in such areas. There is a concern that our sample is subject to geographical bias due to the heavy representation of European wind farms; however, we contend that the global diffusion of wind power has resulted in development cost convergence, attenuating such concerns.

To make the sample of wind projects as robust as possible, no data were excluded. We used what we had access to. The name and exact location of the wind farms have been anonymized due to our confidentiality agreement with the data provider.

A literature study was undertaken to inform the development of four hypotheses. This involved a search of online academic databases. The search was directed through the following keywords: "Wind

Energy," "Wind", "Onshore", "Offshore" and "Wind Power" in combination with "Cost of energy", "Onshore", "Forest", "Offshore" and "Energy production". The search produced an enormous amount of literature, which was further filtered to exclude irrelevant papers with little or no focus on the topic. In the end, we stopped our analysis after reading through 41 papers because these papers revealed four preconceptions related to development patterns of onshore and offshore wind farms that we felt merited analysis.

An important tenet of policymaking is that robust policy cannot be developed until the policy context and the needs of central stakeholders are well understood (Bardach, 2011). This is especially true when it comes to development policy which relies on market incentives to catalyze private sector investment. In development policy, robust policy anticipates industry needs and engenders an environment that resolves barriers to voluntary investment activity (Valentine, 2012). This study embraces the principle that understanding differences in wind farm development patterns yield insights into industry investment patterns which can influence investment activity. Simply put, by understanding how developers are currently structuring wind farm sites – both onshore and offshore – policymakers can then begin to understand what carrots, sticks or sermons are needed achieve wind power diffusion (Bemelmans-Videc et al., 2003).

2.1.3 Four Preconceptions and Four Hypotheses

Based on the literature review, we identified four preconceptions implied in the articles studied, which help to shed light on development patterns for different types of wind farms (onshore, offshore and onshore in forested areas). Verifying these preconceptions will hopefully help us to better understand wind power development patterns preferred by industry, or indeed in some cases patterns colored by policy.

Preconception 1: Stronger and more stable offshore winds enable more wind power production

The rationale for this preconception is grounded in geophysics. First, comparatively strong coastal breezes are created by thermal variations caused by differences in rates of thermal retention between land and sea. Second, onshore winds are more turbulent than offshore winds because onshore winds are influenced by natural (i.e. mountains and forests) and manmade (i.e. buildings) barriers (Wizelius, 2007). Consequently, there is a preconception that better wind conditions offshore, enable the construction of turbines with high wind capture capacities (Bilgili et al., 2011; Troen and Petersen, 1989)

Validating this preconceived notion is important for policymakers because in many advanced wind nations, the superior wind power potential of offshore environments often provides the justification for setting higher offshore development incentives. To test this: *Hypothesis 1: Offshore wind farms will produce more energy per installed MW compared to onshore configurations.*

Preconception 2: Offshore projects must be larger to offset higher investment costs

Most comparative studies acknowledge that offshore projects are currently more expensive on a per kilowatt hour scale than onshore projects. Offshore turbine foundations are far more expensive than onshore counterparts, transmission of collected energy is more expensive due to higher cable costs and the costs of constructing turbines in a marine environment are much higher due to the specialized equipment and unstable construction environment. As a result, Perveen and colleagues (2014) suggest that offshore wind farms should be constructed with a capacity above 1 GW to minimize the capital expenditures per installed MW. This then suggests that offshore wind power projects will be generally

larger than onshore counterparts in order to generate the added revenue to cover higher fixed costs of construction.

Validating this preconceived notion is important for policymakers because if this is true, national wind power planning initiatives should seek to identify offshore sites that will allow developers to offset these higher investment costs. To test this: *Hypothesis 2: Offshore wind farms will produce more energy in aggregate compared to onshore configurations*

Preconception 3: Capacious oceans enable optimized spacing of offshore wind turbines, yielding more homogenous energy production from the installed wind turbines

For developers, the success of a wind farm depends on maximizing profits per km^2 of a given site. This in turn depends on three factors: i) the price at which wind power can be sold, ii) the cost of the turbines and iii) the energy that each turbine can capture. Onshore, the ever-larger wind turbine blades combined with increasing costs and competition for acquiring land have forced the wind industry to decrease spacing between wind turbines, challenging developers to find an optimal balance between maximizing the number of wind turbines while limiting energy losses from wake impediments. Research suggests that wake losses cause substantial energy losses for wind farms (Subramanian et al., 2015). In response, a range of studies have recently been examining approaches to avoid such loss (Göçmen et al., 2016; Son et al., 2014). Despite the importance of this topic, no studies have examined if spacing differences actually occur in practice for wind farm configurations. The logical preconception is that offshore wind farms will exhibit more spacing between wind turbines, due to fewer complications with land acquisition. However, work done by Paul Gipe seemingly contests this notion. Gipe (Gipe, 1995a) argues that successful onshore wind farms attenuate NIMBY opposition through planning that emphasizes aesthetic uniformity and harmonized structures. This seems to suggest that onshore wind farms might actually be planned in a more spatially effective fashion.

Validating the preconception that offshore wind turbines will exhibit greater spatial distance will potentially allow policy makers to better understand the practical spatial challenges that wind power developers face when planning wind power projects. To test this: *Hypothesis 3: Offshore wind farms will exhibit more spacing between wind turbines, and therefore record less variance in energy production from its wind turbines.*

Preconception 4: Technological progress and learning effects are engendering more efficient wind farms

Much has been written on the progressive technological advances being made in wind turbine technology. Between 1994 and 2013, wind turbine generation capacity increased eightfold from under 1 MW to over 8 MW (DONG Energy, 2008). To add to this, improved efficiencies through experience have had a noted effect on bringing down the cost of wind power production (Lindman and Söderholm, 2012). Yet, there is no data on how impactful these trends have been in terms of making wind farms more efficient.

Validating this preconceived notion is important for policymakers because the case for supporting wind power R&D rests largely on the capacity of such investment to enhance the economics of wind power production. Simply put, are technological enhancements and experience truly engendering better wind power developments. To test this: *Hypothesis 4: New wind farms will generate more energy per turbine than older wind farms.*

Table 5 Four Hypotheses on estimated versus actual operational performance from three wind farm configurations.

Preconception	Hypothesis
Stronger and more stable offshore winds enable more wind power production at offshore sites, in comparison to onshore wind farms	Offshore wind farms will produce more energy per installed MW compared to onshore configurations
Offshore projects must be larger than onshore projects to offset higher investment costs	Offshore wind farms will produce more energy in aggregate compared to onshore configurations
Capacious oceans enable increased spacing of offshore wind farms, engendering more consistent energy production for the installed wind turbines	Offshore wind farms will have more spacing between wind turbines; and therefore, record less variance in energy production from its wind turbines.
Technological progress and learning effects are engendering more efficient wind farms	New wind farms will generate more energy per turbine than older wind farms.

Analytical Methodology

In order to process our data, the robustness of the results for the hypotheses will be tested using descriptive statistical analyses in order to test the hypotheses. The descriptive statistical analyses reveals basic measures, such as mean, median, minimum and max values, which makes it possible to compare the configurations for each hypothesis. As advocated by Cohen (1988), graphs and diagrams are also used in the analysis to yield visual insights underpinning the statistics.

In comparing offshore and onshore wind power farms, a decision was made to further analyze onshore farms by delineating them into two configurations – onshore rural sites (i.e. farmlands) and onshore forested sites. This is because it is suspected that the recent trend of developing wind farms in forested areas exhibits development patterns that might be substantially different from onshore rural locations. There is a concern that in aggregating the onshore data, the new forested developments will confound the results. Therefore, we have elected to address this threat to internal validity by separating the onshore datasets.

Understanding how different variables influence the configuration of wind farms is important from both commercial and public policy perspectives. From the commercial side, smaller wind farm developers would benefit from a more informed understanding of what configurations might work best under various siting options. For policymakers, understanding how projects are currently configured in response to various siting scenarios is a critical first step to designing policy to induce targeted development. In response, we have attempted to conclude the study with an analysis of what our findings mean for policymakers.

2.1.4 Results and Discussion

The graph in Figure 4 presents the total number of wind farms, 44, and their annual production (MWh) per installed MW in 2015. The highest production from a wind farm was 4856 MWh per installed MW, and the lowest production was 1867 MWh per installed MW.

Figure 4 The combined dataset
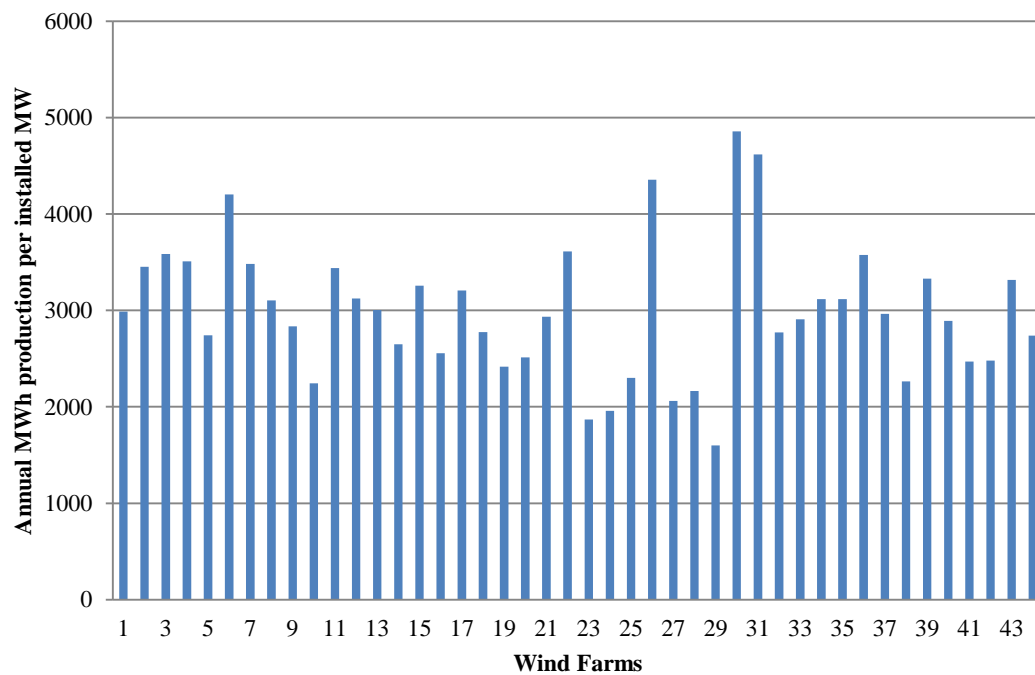
Figure 5 The configurations
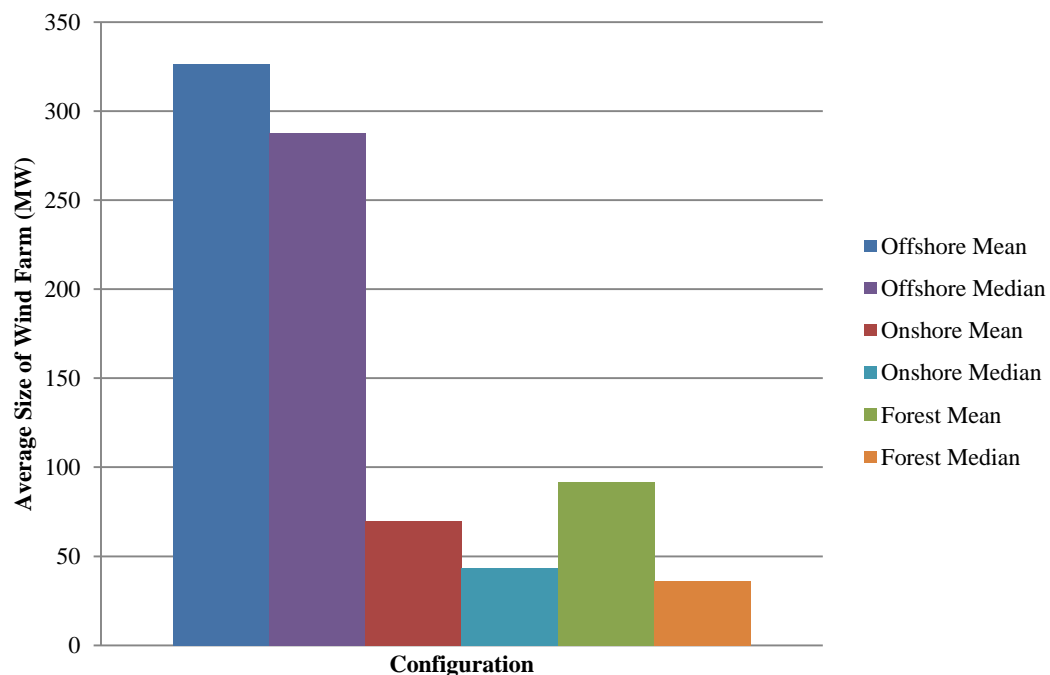
Figure 5 summarizes the average wind farm size for each of the configurations studied in this article. The offshore wind farms are, on average, largest with an average of 326 MW installed (and a median of 288 MW), far eclipsing the mean size of onshore wind farms of 70 MW (and median 43.5 MW). This reflects a global trend that sees offshore wind farm sizes continuing to outpace onshore counterparts (CarbonBrief, 2015). The wind farms deployed in forests have a mean size of 91 MW, yet, this is due to one large project on nearly 500 MW, which also is highlighted by a mean value of

36 MW. After describing the results, section 4 will highlight the more significant findings and discuss their implications.

Hypothesis 1: Offshore wind farms will produce more energy per installed MW compared to onshore configurations

The first hypothesis tests a well-travelled assumption related to wind quality. We postulate that offshore wind farms will have a higher annual energy production per installed MW than onshore configurations. The rationale is that offshore wind farms are presumed to be strategically sited in locations with higher and more consistent wind quality (Archer and Jacobson, 2005; Perveen et al., 2014). Additionally, it is believed that offshore projects are typified by turbines that are separated by greater rotor distance ensuring a lower wake loss.

In undertaking our analysis, the two predominant onshore developments (onshore rural and onshore forested) have been disaggregated and compared to the offshore wind farms. When comparing onshore sites, wind projects located in farmlands are expected to record higher annual energy production per installed MW compared to the onshore wind projects in forested areas, due to the impact from the forest on the wind conditions, which in most cases would decrease the mean wind speed in the wind turbine's swept area and increase the turbulence level (Enevoldsen, 2016; Bergström, et al., 2013).

The descriptive statistical analysis performed in Table 6 presents the results from the dataset, which suggests that offshore wind farms have a mean higher energy production per installed MW compared to the means from onshore wind farms and onshore wind farms in forests. The mean energy production per installed MW for offshore sites was 3234 MWh in 2015, for onshore rural sites the number was 2890 MWh, and for onshore forested sites, the production per installed MW was 2918 MWh,

Table 6 Descriptive statistical analysis of Hypothesis 1

Offshore MWh Per Installed MW	
Mean	3234.386013
Median	3437.765615
Standard Deviation	524.674784
Minimum	2243.023163
Maximum	4203.705913
Onshore MWh Per Installed MW	
Mean	2890.893677
Median	2712.094106
Standard Deviation	903.8255515
Minimum	1599.334783
Maximum	4856.086957
Onshore in Forest MWh Per Installed MW	
Mean	2918.220735
Median	2908.754738
Standard Deviation	378.2891664
Minimum	2264.818097
Maximum	3576.091112

However, closer analysis of Table 6 reveals that the difference might not be statistically significant. As the Table indicates, offshore wind farms included in the study posted a standard deviation of 525 MWh, while onshore rural sites in the study exhibited a standard deviation of 904 MWh. The inference here is that some onshore rural sites might outperform some offshore sites by a significant margin. Therefore, the result cannot be generalized to an extent to allow us to confirm the hypothesis. Indeed, upon analysis of the data from individual wind farms included in the data set, some onshore rural were indeed producing far more power than some onshore sites, as depicted in Figure 6. The three projects with the highest energy production (MWh) per installed MW are onshore projects. It also merits noting that contrary to our expectations, onshore forested sites produced, on average, more energy per installed MW and exhibited far lower variance in power output.

Figure 6 Comparing energy production from three configurations
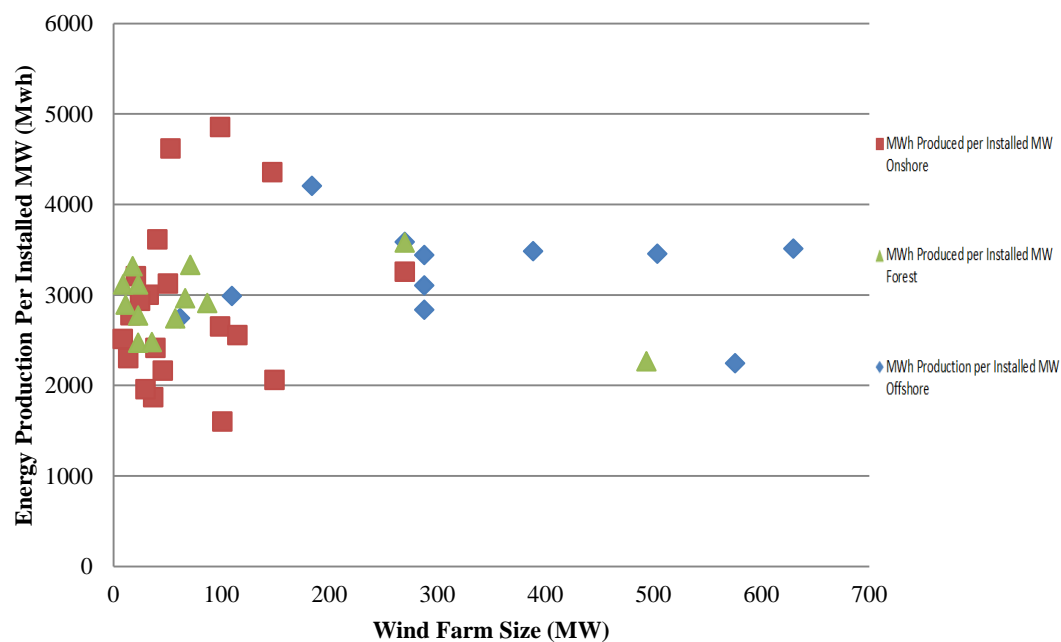
One of the possible interpretations of the data presented in Table 6 is that the varied size of projects might skew the results because larger onshore sites might have been sited in areas of preferred wind conditions. Conversely an alternative and contradictory perspective might also be true – offshore sites are comparatively more expensive so offshore projects are not selected only on the basis of wind quality, they are also selected according to lower siting and transmission & distribution costs. In order to test the theory that scale might influence the amount of energy produced per installed MW, we analyzed statistics to test the correlation between wind farm size and produced energy per installed MW. As the data depicted in Figure 6, there appears to be no statistically significant relationship between wind farm size and produced energy per installed MW, amidst the wind farms included in our dataset.

The results of our analysis contradict conventional belief. The difference between energy produced by offshore and onshore turbines has previously been assumed to be up to 150% in the favor of offshore wind farms (IEA, 2008). Yet, our analysis appears to indicate that if any difference does exist, it is negligible. The reason for a smaller energy production gap might stem from the fact that service and

maintenance offshore requires more downtime than for onshore wind projects, due to the challenges of transportation at sea (Koch, 2014).

Nevertheless, these findings are significant in light of a recent report from the U.S. Energy Information Administration (EIA) which predicted the 2020 levelized cost of different energy technologies (EIA, 2016). The report suggests that the average cost per produced MWh from offshore would be $196.9 – far higher than the $73.6 predicted for onshore wind energy. This suggests that offshore wind energy will be 2.67 times more expensive than onshore wind energy. Therefore, combined with the apparent risks of cost overruns and the higher installation costs, one is compelled to ask whether the extra energy production justifies the added investment. Of course, energy produced per turbine represents just part of the investment rationale for preferring offshore projects to onshore projects. Another influential factor is aggregate energy production. After all, if a wind farm produces slightly less energy per turbine but far more aggregate energy, the contribution to fixed development costs could be greater, thereby, justifying the project.

Hypothesis 2: Offshore wind farms will produce more energy in aggregate compared to onshore configurations

In order to test the proposition that wind farm size is what drives offshore investment, we performed an analysis aimed at addressing the hypothesis that aggregate energy production from offshore wind farms will be greater than from the two onshore configurations. This is based on the preconception that offshore wind farms are not as spatially constrained as their onshore counterparts and offshore projects must have a larger critical mass to cover the extensive fixed costs associated with connecting offshore projects to onshore grids. Figure 6 implies that this is the case, but we wanted to evaluate this in greater detail because confirming such a hypothesis supplements the wind quality findings of Hypothesis 1 with a finding that offshore farms are of greater scale. In short, these two findings would confirm that developers prefer larger scale offshore wind farms to offset the higher investment costs. The descriptive statistical analysis performed in Table 7 presents the results from the analysis.

Table 7 descriptive analysis of aggregate energy production

Offshore Cumulative Wind Farm Production (MWh)	
Mean	1048835
Median	967971
Standard Deviation	586159
Minimum	169975
Maximum	2210852
Onshore Cumulative Wind Farm Production (MWh)	
Mean	211887
Median	123788
Standard Deviation	223609
Minimum	22614
Maximum	879221
Onshore in Forest Cumulative Wind Farm Production (MWh)	
Mean	256386
Median	89211
Standard Deviation	358199
Minimum	28661
Maximum	1118820

The descriptive analysis in Table 7 confirms that the offshore wind farms in our dataset produce far higher aggregate energy production (MWh). The offshore wind farms produce over four times the mean aggregate production from onshore sites. Moreover, a comparison of the standard deviations associated with these three configurations suggests that aggregate wind power production associated with offshore wind farms is far more consistent than the two onshore configurations. For offshore wind farms the standard deviation is 56% of the mean; however, for onshore rural wind farms the standard deviation is a remarkable 106% of the mean and for onshore forested area wind farms the standard deviation is even higher – 140% of the mean. From this analysis, we can confidently conclude that there is strong evidence which supports our hypothesis that offshore wind farms produce more energy in aggregate that onshore wind farms do.

We wanted to test this hypothesis with added rigor and so decided to also evaluate the strength of the relationship between aggregate energy production and wind farm size. Doing so would help us attenuate any threat that differing wind quality patterns were acting as a confounding factor in our analysis. Figure 7 presents the relationship between installed MW and energy production (MWh) for the 44 wind farms.

Figure 7 The relationship between wind farm size and energy production
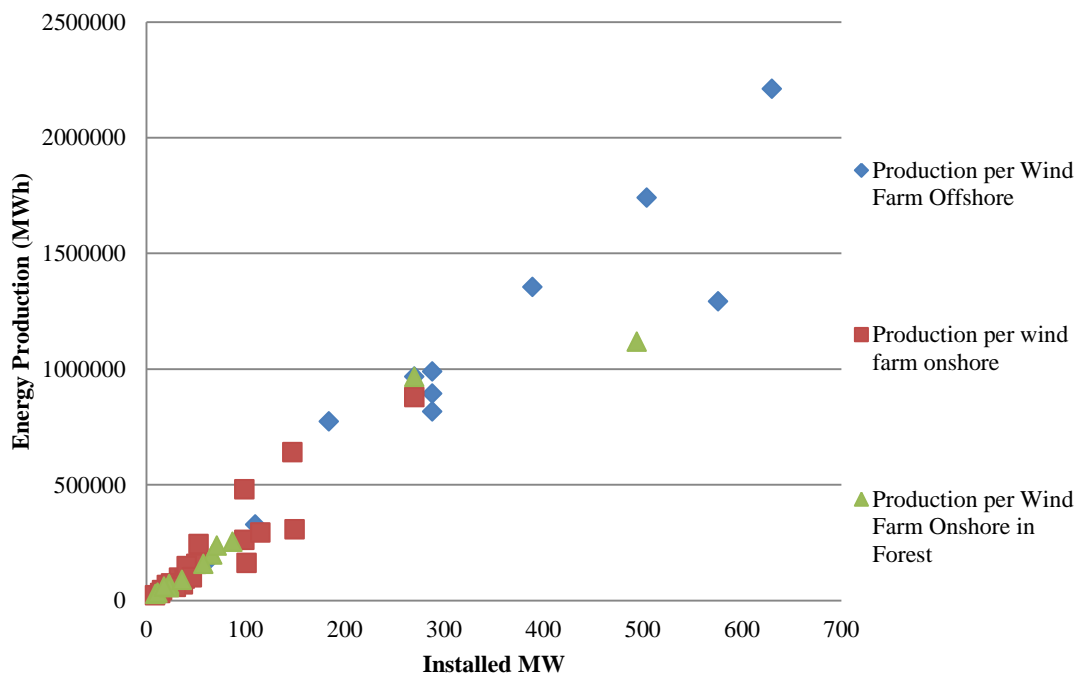
Figure 7 reveals a strong correlation exists between installed wind power capacity and aggregate energy production. . Therefore, we feel justified in concluding that forces catalyzing the development of comparatively large offshore wind farms are not as much based on superior wind quality (refuted through hypothesis 1) but rather is likely due to a need to recoup higher fixed investment costs associated with offshore projects.

However, the higher standard deviations associated with onshore projects outlined in Table 7 gives rise to a new conundrum: Is the enhanced reliability of aggregate wind power production in offshore environments attributed to more stable wind flow patterns or does the marine environment allow for

more dispersed spacing, thereby enhancing wind quality by reducing wind shear? To answer this question, we turn to hypothesis three.

Hypothesis 3: Offshore wind farms will have more spacing between wind turbines, and therefore exhibit less difference in energy production from its wind turbines

The third hypothesis evaluates the preconception that offshore wind farm turbines are spatially less concentrated than onshore wind farms. Consequently, offshore turbines will be less susceptible to wake effects that degrade wind quality. In other words, this hypothesis, if true, explains in part why the standard deviation of power production for the offshore wind farms including in our dataset is lower (as a percentage of the mean output) than the standard deviation of power production for the onshore wind farms.

In order to test this hypothesis, we first needed to collect data on turbine spacing within wind farms. However, a complicating factor emerged – for all wind farms in our dataset, the spacing between turbines was not uniform. Therefore, to derive a standard measure for comparison, the median difference for highest and lowest spacing for all the wind turbines within each wind farm was calculated. Another complicating factor was that the turbines varied by rotor diameter and this difference had the potential to confound the results because offshore wind turbines that are typically of higher installed capacity would automatically require greater spacing. In order to adjust for this factor, distance was calculated as a factor of the rotor diameter.

Figure 8 graphically depicts the relationship between the mean energy output (MWh) per wind turbine and the mean spacing (adjusted for rotor size) for the wind turbines of the wind farms. It merits noting that due to insufficient information on the wind turbine coordinates, only 28 wind farms have been analyzed for testing this relationship.

Figure 8 The relationship between energy output (mwh) and spacing (rotor diameter)
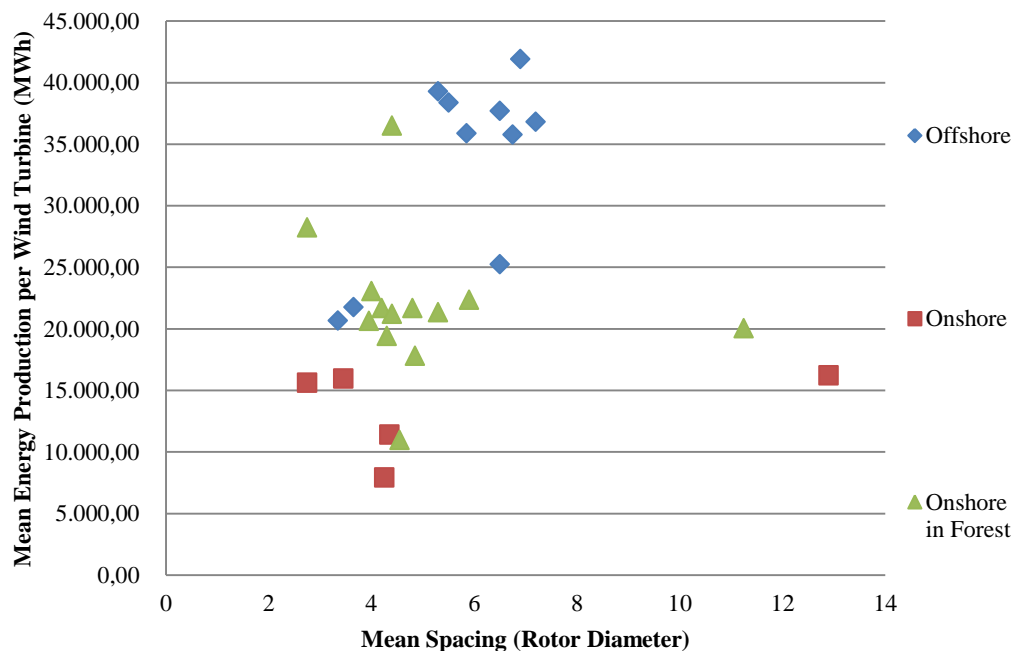
The data presented in Table 8 verifies the first part of hypothesis 3 - the spatial separation between offshore wind turbines is less variable but higher, when compared to the onshore configurations. Next, we turned to the question of whether or not the greater spatial spread of offshore wind turbines gives rise to more consistent power production.

Table 8 Minimum and maximum turbine spacing

	Median for minimum spacing (as a factor of rotor diameter) – meters	Median for maximum spacing (as a factor of rotor diameter) - meters
Offshore farms	5.15	6.80
Onshore farms - rural	3.3	5.4
Onshore farms - forested	3.6	5.2

Previously, we produced results of power production in Table 6. In Table 9, we have reproduced this data along with the data on wind farm spacing to get a feel for whether or not increased spacing of turbines is correlated to reduce energy production variance. As Table 9 suggests, if we were to take the average of the minimum and maximum spacing means of the wind farms, offshore turbines in our dataset can be said to exhibit greater spatial distance than either of the onshore configurations. As the power variation column indicates, energy production variation at onshore rural locations is significantly higher than the power variation at offshore farms. Therefore, there is evidence that our hypothesis might be valid when comparing onshore rural sites to offshore sites. However, when onshore forested sites are evaluated on the same metrics, it is apparent that the forested onshore sites included in our dataset actually exhibit less power variation than offshore sites, despite having turbines that are, on average, approximately 36% more concentrated in terms of spatial placement. These contradictory findings lead us to question the validity of our hypothesis and seek more definition in our statistical analysis.

Table 9 Power Variation vs. Turbine Spacing

	Mean (MWh/ installed MW)	Standard Deviation (MWh)	Power Variation (SD as % of Mean)	Mean of min/max spacing (as a factor of rotor diameter) - meters
Offshore farms	3234	525	16.2%	5.98
Onshore farms - rural	2891	903	31.2%	4.35
Onshore farms - forested	2918	378	13.0%	4.40

When examining Table 9, it becomes clear that there is no correlation between power variation and turbine spacing. An obvious question that should arise from the data presented in Table 9 is what causes the stark contrasts? If we tested offshore farms versus onshore rural farms only, we might conclude that greater turbine spacing does indeed contribute to attenuating energy production variances. However, the onshore forested wind farm dataset contradicts this conclusion and forces us to consider why the two onshore configurations exhibit such a stark contract when it comes to power variation, despite exhibiting similar profiles when it comes to turbine spacing. Indeed, one would be tempted to conclude that the results in Table 9 for the onshore configurations contradict the popular

conception that wind farms placed in forested areas suffer from poorer wind quality due to the turbulence engendered by the trees.

One possible explanation for this puzzling result is that the forested onshore wind farms are a relatively new phenomenon. Accordingly, these farms would likely be constructed using the most advanced wind power systems in preferred locations. As a result, the turbines within the wind farms in the forested areas will be more efficient at capturing better quality wind, when compared to the older turbines that one would likely find within the rural onshore wind farm locations. In explaining why the power variation in forested onshore locations is better than the power variation in offshore locations one might hypothesize that both configurations use newer and more efficient technology but the forested locations suffer from less downtime than do the turbines that are sited in marine environments. To evaluation this notion, we turn to hypothesis four.

Hypothesis 4: New wind farms will generate more energy per turbine than older wind farms

The fourth hypothesis evaluates a preconception that is both intuitive and grounded in published literature – new wind farms will generate more energy per turbine than older wind farms will because of improved technology and learning by doing efficiencies. The arguments in support of this notion stem from the observed trend of wind turbines becoming more efficient due to increased knowledge of siting (Sahin, 2004), innovations to the control systems and generators, the increased height of the towers, and the increased size of the wind turbine blades (Manwell, 2009). According to popular consensus, these developments allow the modern wind turbine to produce more energy per installed MW than its predecessors. According to one study in 2009, a wind turbine produced in that year would generate 180 times more electricity when compared to 20 years before, at less than half the cost per produced MWh (Blanco, 2009). Compared to turbines manufactured just 25 years ago, modern turbines are four times larger. The maximum rotor diameter has increased to more than 100 meters and the maximum hub height has grown to more than 70 meters (Paulsen and Thüring, 2015). This change in wind power system size and know-how is considered to have increased the efficiency per installed MW, despite the fact that the generator size (MW) of the wind turbines have increased as well.

We began to test this hypothesis by conducting a statistical analysis than correlated energy production on an installed MW basis with the year that the wind farm was built. Figure 9 graphically illustrates the distribution of the dataset, where the bubbles represent the cumulative energy production (MWh) per wind farm.

Figure 9 The technological innovation learning effect
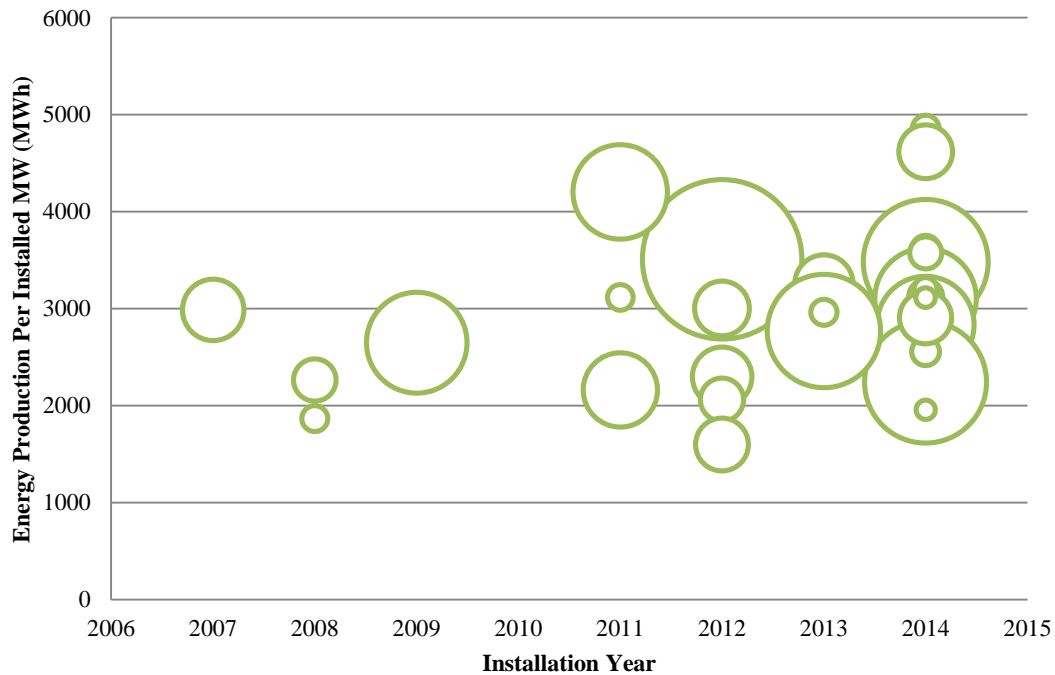
It might be apparent from the graphic depiction of the dataset in Figure 8 that there is not a decisive trend that supports the hypothesis. Compared to the energy production from the wind farms that were established in 2007 (3,000 MWh per installed MW), some turbines from subsequently sited wind farms are clearly producing more power per installed MW, while other wind farms are less effective.

As Figure 9 indicates, there appears to be little relationship between the year of installation and energy production from the wind farms in our dataset. In evaluating this data, it was feared that configuration (onshore, onshore-rural, onshore-forested) might be a confounding factor. For example, if one configuration were dominant in early years and another configuration were dominant in later years, the results might be skewed due to selection bias (Cook and Campbell, 1979). Therefore, another statistical analysis was run whereby the data was segregated by configuration type. Figure 10 provides a graphic depiction of the data. Once again, one can readily see that an upward trend that would indicate a positive innovation effect is not visually evident. To be empirically certain, we also ran a statistical analysis delineated by the three configuration types.

Figure 10 Innovation effects for each configuration
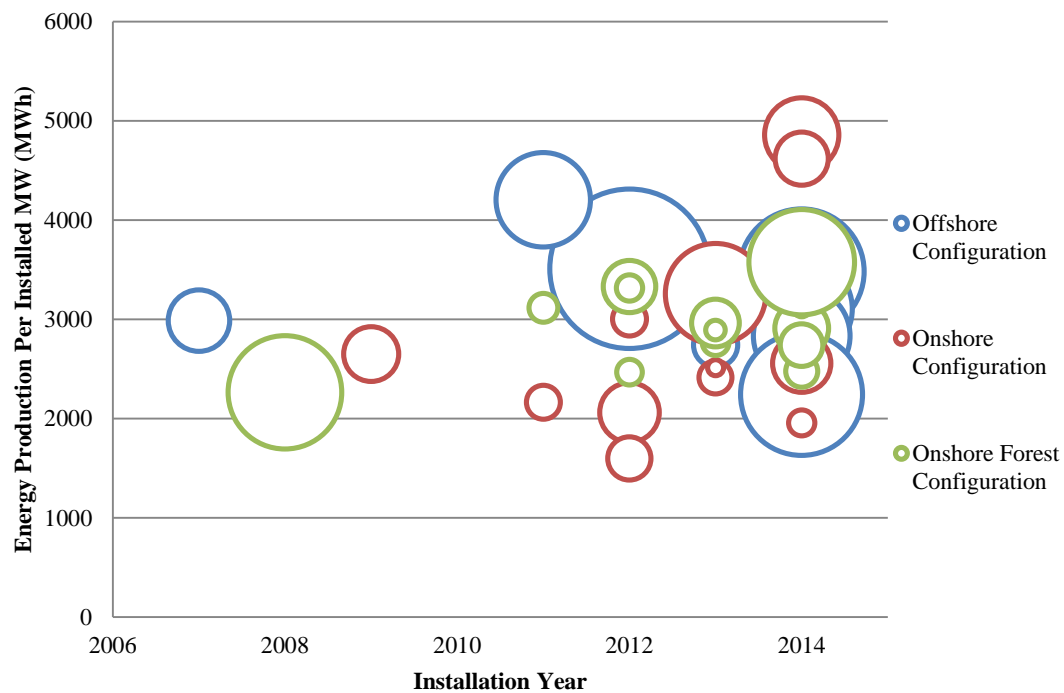
When separating the data based on the three configurations, it becomes clear that there might have been a slight selection bias in the data. The coefficient for offshore wind farms is negative suggesting a regression in turbine efficiency while the onshore configurations exhibited a positive correlation, suggesting improved turbine efficiency. However, we cannot validate our hypothesis that newer wind farms produce energy more efficiently.

With that said, there are a couple of threats to validity that must be noted for this hypothesis test. First, we have used the year of wind farm establishment as a proxy for the age of the turbines. This might not be true as wind farm developers might not install the newest turbines. Although we contend that the global shortage of wind turbines has created market conditions whereby turbines that are manufactured go almost immediately into service, this cannot be ascertained with the data that we have; and therefore, the concern remains as a threat to construct validity. Second, it might very well be that the onshore-rural configuration is the only configuration that can be validly used to evaluate our hypothesis. This is because the offshore and onshore-rural configurations reflect relatively new siting options and the relatively low coefficients associated with these configurations might simply reflect project teething pains. In short, there has not been enough learning for a learning effect to be ascertainable. On the other hand, onshore rural wind farms are well established and mature. Therefore, these farms would be most likely to exhibit positive efficiency progress caused by learning by doing and improved technology.

2.1.5 Discussion on findings

The following section summarizes the results of the tests conducted for the four hypotheses. The results of examining the hypotheses have been summarized in Table 10 below and a brief discussion of the implications of these findings will follow.

Table 10 Summarizing hypotheses results

Hypothesis	Tested by	Hypothesis Supported/ Unsupported	Effect
Offshore wind farms will produce more energy per installed MW compared to onshore configurations	Descriptive statistics analysis	Unsupported	The analyses revealed very low coefficients of determination, suggesting that the correlation between energy produced on a per MW basis and site configuration is not supported by the data.
Offshore wind farms will produce more energy in aggregate compared to onshore configurations	Analyses of variance Descriptive statistics analysis	Supported	The preconception was validated, as offshore wind farms in the dataset produced far more energy than its onshore counterparts. The descriptive statistics analysis revealed that offshore wind farms are generally larger, which is the main catalyst behind greater energy production.
Offshore wind farms will have more spacing between wind turbines, and therefore less difference in energy production from its wind turbines.	Analyses of variance Descriptive statistics analysis	Unsupported with an exception	The precondition was not supported. Although offshore wind farm turbines did exhibit greater spacing between units, this did not translate into diminished power variation when compared to the onshore forested sites. There was however loose support for the claim that offshore wind turbine exhibit greater spacing and lower power variance than onshore rural turbines.
New wind farms will generate more energy per turbine than older wind farms.	Analyses of variance Descriptive statistics analysis	Unsupported	This preconception was also not supported by the data. The statistical analyses indicated that the correlation between turbine power generation and turbine age was not strong. Indeed, a negative trend was ascribed to offshore turbines.

The results presented in Table 10 show that only one of our hypotheses was supported by the data from our dataset. If our data is representative of the broader universe of wind farm data there are some interesting ramifications associated with these findings. However, before we turn to an analysis of the implications of our findings, it merits highlighting some of the potential threats to validity associated with our analysis.

Overall, there were a number of threats to validity that can be attributed to the study, all stemming from the unique nature of our data. In many quasi-experimental studies, threats to validity are attenuated through strategic research design. However, in this study, the analysis was entirely dependent on a dataset that was provided by the industry. We could not supplement this data with our own primary observations because of the geographic dispersal of the sites, budget constraints and site access limitations (because the sites were private property). Therefore, when it came to manipulation of the data, we tried to ensure that no data were excluded in order to avoid this form of selection bias (Cook and Campbell, 1979). Nevertheless, despite our best efforts, there are some threats to validity that simply could not be removed due to the nature of our data.

In terms of statistical conclusion validity, there were two basic concerns. First, the geographic settings of the wind farms are not homogeneous. The sites vary significantly in terms of terrain, physical impediments, surrounding environment, climactic patterns, and wind quality. Unfortunately, there was not enough data on the specific sites to avoid this threat known as *extraneous variance in experimental settings* (Cook and Campbell, 1979). Although we contend that the large number of windfarms (44) included in the dataset help to somewhat attenuate this threat, more data on the physical features of these sites would be necessary to fully alleviate this concern. Second, both within windfarms and between windfarms, the turbines that were used for generating the electricity were heterogeneous – differing in terms of nameplate power output and turbine features, such as variable gears or blade sizes. Because the technology differs, this introduces a threat to validity known as *heterogeneity of units* (Cook and Campbell, 1979). Again, it would be useful to validate the results through comparisons of wind farms employing similar turbine technology; however, in practice this is not feasible. Turbines are chosen specifically to optimize the unique characteristics of the sites. Once again, we contend that the analysis of numerous windfarms inject a degree of representative validation into the study, but the threat remains and cannot be attenuated.

In regard to internal validity, there are two main concerns. First, although the data set included turbines from all around the world, the vast majority of the wind farms from the dataset are located in Europe, injecting a degree of geographic bias into the sample. Only further testing using wind turbines from different sample sets will mitigate this threat; therefore, this represents an avenue of future research. Second, there might be an *additive threat* associated with this analysis in that wind farm developers tend to upgrade their infrastructure over time. Turbines are refurbished, new transformers are added and improvements to the maintenance schedule are made. Therefore, these phenomenon are threats to our fourth hypothesis which postulates that new wind farms will generate more energy than older wind farms on a per megawatt basis. In order to attenuate this threat, data would be needed on maintenance schedules, part replacements and infrastructure upgrades. This is data that we did not have. However since this threat applied mainly to the fourth hypothesis, and would likely be of limited impact because of the number of wind farms included in this study, we simply conclude that analyzing the technical evolution of existing wind farms represents a promising area for further research.

In terms of construct validity, there is a concern that in testing the fourth hypostasis that our decision to use the age of the wind farms as a proxy for the age of the turbines on the wind farm will not be accurate. Older wind turbines might be purchased from suppliers or, as mentioned in the previous paragraph, existing turbines might be upgraded over time. These factors would skew our results and invalidate the proxy. In order to attenuate this threat to construct validity, we would need more detailed information on when each turbine was manufactured. This is information that we did not have and so we have absorbed some risk in our construct strategy. The fourth hypothesis was not

supported. However, if the hypothesis was not supported because older windfarms were upgraded with newer turbines, then the results of our analysis have been confounded. Once again, this concern can be vetted in the future through follow-up studies using the manufacture date of turbines, if available.

Regardless of these extant threats to validity, we contend that this study still exhibits a high degree of predictive validity, particularly in regard to the first three hypotheses which would not be significantly impacted by any of these threats to validity because the relatively large sample size of wind farms would help to dampen any confounding threats. This study is the first of its kind and employs proprietary data in order to undertake the analysis. It is a unique situation where, as researchers, we do not have full control over our data collection strategy. Therefore, there are bound to be threats to statistical conclusion, internal and construct validity. Over time, as more data are made available to researchers, these findings can be supplemented and verified to a higher degree of certainty.

With these threats to validity in mind, we feel that we can now turn to a discussion of the findings that we feel represents externally valid conclusions.

The Realities of Offshore Wind Farm Power Production

Contrary to popular belief, our data set suggests that enhanced wind quality - commonly attributed to offshore wind farms - does not necessarily translate into improved power production per MW of installed capacity. This is a remarkable finding because the power of wind is proportional to the cube of the wind speed (Wizelius, 2007); and it has widely been assumed that offshore winds are both stronger and more consistent. Consequently, turbines at offshore wind power sites should produce significantly more energy on an installed megawatt basis.

In order to find out why this is the case, further research is needed. We posit that there are four possibilities that might explain why offshore wind power does not live up to its billing as a vastly superior wind force. First, although it is true that offshore winds might be less turbulent due to the absence of geographic figures that might cause additional wind drag, this difference might not make much of a difference with the modern variable gear turbines. Second, the strength of offshore winds tends to be heavily influenced by sea and land breezes caused by thermal retention variances between the ocean and bodies of land. Therefore, although offshore wind speeds might be higher than onshore wind speeds at times during the day, they might not be vastly superior over the duration of the day, and as a result, the impact might be negligible. Third, due to operating in a harsher marine environment, offshore wind turbines might experience more downtime than their onshore counterparts, and as a result, each turbine might produce less energy over the course of a year.

Regardless of the cause of this outcome, it is clear that given the higher construction costs associated with offshore wind farms, developers cannot count on preferred wind conditions to enhance the economic attractiveness of their offshore development projects. Instead, developers need to focus on offsetting the higher construction costs through larger windfarms. Indeed, our data set supports this conclusion. Although offshore wind farm turbines did not produce more energy on a per megawatt basis, the offshore wind farms produced far more energy in aggregate simply because they were so much bigger than their onshore counterparts.

There's a lesson here for policymakers as well. Since developers require larger tracts of offshore seabed to their investment, policymakers should be aware of the implications in regard to managing public acceptance of these types of projects. It may very well be that certain sites, where aesthetic

concerns are less of an issue, might need to be prioritized in order to avoid levels of public opposition that might derail project development.

The Promise of Onshore Wind Farms in Forested Areas

On one hand, our data set confirms the preconception that the unfettered capacious seabed means that offshore wind sites allow developers to increase spacing between the turbines. On the other hand, this does not translate into less power production variance, when compared to onshore wind farms in forest areas. This is a remarkable finding because it suggests that offshore wind farms might not be the only attractive option for increasing installed wind power capacity without engendering public opposition. Our data set suggests that onshore wind farms can be developed in a more concentrated manner and still produce a more consistent power output portfolio than offshore wind farms.

We consider it to be remarkable that onshore wind farms in forest areas, which are subject to large scale wake effects due to the physical disruption that the forest has on wind patterns, exhibit such high levels of consistency when comparing minimum and maximum energy generation profiles. Therefore, our finding gives rise to questions on: i) current assumptions related to large-scale weight affects (for offshore wind farms, enhanced spacing between turbines does not appear to significantly enhance power output) and ii) current assumptions related to the impact that trees have on wind effects. Indeed, in regard to the latter question, we wonder if it is not possible that, like mountain ranges, some forest formations actually force winds upward, thereby enhancing wind conditions at higher altitudes, which can be captured due to the increased hub heights for wind turbines installed in forests. More research is required in this regard but our initial finding clearly suggests that onshore wind farms in forested areas represents the best of both worlds, attractive wind conditions without the high costs of developing wind farms in marine environments.

New is not necessarily better

When wind energy experts talk about the future promise of wind power, they're quick to point out that each successive generation of wind turbine is capable of capturing far more energy than older models are. Since energy capture is directly influenced by the windswept area of the turbine, it is difficult to argue against this assertion. However, the findings from our research suggest that these benefits might not be immediately realizable when it comes to the adoption of new technology. Our data set suggested that new wind farms do not necessarily generate more energy on a per installed megawatt basis.

There are a few factors that we can speculate on as the cause for this. The first is our previously mentioned concerned that the proxy we used to define the age of a turbine (which was the establishment date of the wind farm) might not be accurate. It may very well be that turbines on older windfarms have been upgraded and this would confound our estimate of age. Another potential causal factor is that newer models do not enjoy the same level of field-tested reliability that the older models enjoy. As a consequence, newer models break down more often and this added downtime reduces aggregate annual output per turbine. Finally, another potentially confounding factor in regard to our finding here is that older wind farms are typically established at sites that are most preferred when it comes to wind quality. As these older sites become saturated, developers start to move to other sites that might not necessarily be as attractive. This has been demonstrated in Taiwan (Valentine, 2010). Clearly further research is merited in order to try to understand further why turbines that on paper should generate more energy per installed megawatt do not achieve this level of performance in real life.

2.1.6 Conclusion and Policy Implications

This research has examined three wind farm configurations, (1) Offshore, (2) Onshore in rural areas, and (3) Onshore in forests, in order to gain developmental insights into energy productivity. Four preconceptions and hypotheses were constructed based on previous contributions from scholars and industrial reports, and analyzed using a dataset consisting of 44 farms, all with operational data for 2015. By doing so, this research reveals not only the latest trends in the wind industry but also yields information on challenges and opportunities for future installations of wind farms. Although our conclusions face some threats to internal and external validity due to the nature of the proprietary dataset that we were working with, the statistical evidence from such a large dataset suggests that further studies will likely validate our findings.

In closing, it is clear that the answer to our research question – "Do onshore and offshore wind power development patterns differ" – is a resounding yes. Offshore wind farms are characterized by turbines that are more widely spaced and they are much larger entities – generating far more power in aggregate than onshore counterparts. However, this appears to be motivated by a desire on the part of developers to offset higher offshore wind farm costs through larger farms. This does not mean that the wind quality is actually better.

Indeed, the most significant finding was the evidence from the dataset that offshore wind power is not as superior as perhaps it has been billed. There is evidence that onshore wind farms constructed in forested areas might be a preferred alternative when the higher costs of offshore wind power are factored in. Clearly, the performance of onshore wind farms in forested areas merits closer study.

2.2 Onshore wind energy in Northern European forests: Reviewing the risks

This study reveals the risks for wind energy in Northern European forests, covering UK, Norway, Denmark and Sweden. The paper is based on an extensive synthesis of more than 100 peer-reviewed studies, and explores the risks associated with onshore wind energy in forested areas in Northern Europe. The analyses are performed using a risk management model to conduct a comprehensive literature review on onshore wind energy in such areas. Using an innovative division of a wind turbine's lifecycle and risk categories, this study provides a complete overview of the present academic literature on the risks associated with wind energy in forested areas. Consequently, this study contributes to the wind industry in terms of the risks to be considered for onshore wind projects in forested areas in Northern Europe and to inform the debate in the energy studies literature concerning the lacks and explanations regarding the risks currently covered by the academic literature. The comparative analysis performed in this research reveals trends in the literature and their implications for time and phases of research. The scholarship contribution to the research topic have been compared to geographic specificities and country profiles for each of targeted countries in Northern Europe, resulting in a complete overview and introduction of the risks associated with onshore wind energy in forested areas in Northern Europe.

2.2.1 Introduction

Human kind has been harvesting the wind to create energy for multiple purposes since roughly 3000 BC (Hills, 1994; Sahin, 2004),with the production of electricity being the latest trend. The deployment of wind turbines has increased dramatically in recent decades in Northern Europe (Manwell, 2009; Christie & Bradley, 2012; Szarka, 2007), as green energy policies have created a market for renewable energy (Szarka, 2007; Tabassum-Abbas, et al., 2014), mainly due to the fact that global warming and climate change have been accepted as posing a severe threat to the inhabitants on earth (Zhang, 2008). More than two decades ago, Grubb and Meyer (1993) estimated the global potential for installed wind capacity to be 53,000 TWh/annually when considering the environmental and land use constraints. Since that study, however, the potential wind capacity is expected to have increased, as the general wind turbines have increased in size (Wizelius, 2007). The increased wind turbine hub height (Manwell, 2009; Leung & Yang, 2012) has rendered it possible to position wind turbines in forested areas. Moreover, wind project developers in Northern Europe have been forced to locate wind farms in forested areas and offshore due to the lack of space (Manwell, 2009; Wizelius, 2007) and rising land prices (Bergström, et al., 2013). Yet, offshore wind projects often requires larger investments and comes with a greater risk of cost overrun both during the construction and in the operational phase of the wind turbine's life cycle (Heptonstall, et al., 2012; Zwaan, et al., 2012). Besides acquiring land at cheaper prices, wind turbines in forested areas are generally expected to be deployed far from residential areas, which reduce the negative aspects of wind turbines such as visual impacts and noise emissions, and a study conducted a decade ago by the National Renewable Energy Laboratory (2005) revealed the great potential of deploying wind turbines in forests. This is considered a mentionable strength of wind turbines in forest. On the downside, wind turbines requires space both for the wind turbine itself but also for road connections, cables, equipment required for the installation etc., which may have a negative impact on the local forest environment, due to the felling of trees and interference with the animal life. Therefore, it should be sought to limit the felling of trees. However, from an efficiency point of view, it comes as no surprise that the presence of trees creates a demand for a higher hub height, which adds costs in the production of the wind turbines, due to the need for higher towers. However, even when taking this

need into consideration, wind turbines deployed in forested areas risks a lower life time and less energy production, due to the increased turbulence intensity and wind shear (Wizelius, 2007).

In the initial search for literature it was found that a range of academic papers have been studying risks for onshore wind projects in general. However, few studies, if any, have adequately explored the risks related to wind farm development in European forests. The analysis of the performed literature review in this study reveal lacks of peer reviewed literature for several risk parameters.

In response to this apparent lack of research, this paper will review and explore the complete array of risks associated with developing wind farms in forests in the United Kingdom (UK), Denmark, Sweden, and Norway. The reasons for targeting exactly these countries are explained in details in 2.2.2.3, the main aspect is of course the fact that each country has enormous areas covered by forest where wind turbines can be deployed to harvest the strong winds in this region of the World (Troen & Petersen, 1989). By investigating the research topic using a holistic risk framework, this study aims at revealing the risks and introduce how the literature's contribution on risks have changed over time in relation to the developed wind capacity in the targeted countries. Clarification of the risks associated with wind energy production in forested areas is required to support the continued development of wind energy in Northern Europe, which this research seeks to cover by introducing the technical risks during the wind turbine's life cycle. However, a continuation of the positive trends of wind energy in Northern Europe is only possible with sociopolitical acceptance of wind turbines in forests, why the results explored in this research also are expected to affect the energy policy in the targeted countries. The cost of protecting the earth from climate change has been studied extensively and will be investigated in this research, with a specific focus on revealing the risks of local negative impact on wind projects. Summing up, this research will present the most comprehensive risk overview ever published for wind turbines in Northern European forests through the following contributions:

- An overview on existing literature targeting risks for wind turbines in forested areas in Northern Europe
- An introduction to risks, which stakeholders in the wind industry in Northern Europe needs to consider
- An overview on whether and potentially how the existing literature covers these risks sufficiently
- An overview of the development of academic contributions as a function of the installed capacity in the targeted countries
- An overview on the risks, which future studies needs to target.

2.2.2 Research material and methods

This section of the study presents the methods and materials used to analyze the risks associated with wind turbines in forested areas in Northern Europe.

2.2.2.1 Risk framework

This study proposes a risk framework consisting of 10 risk parameters divided into three phases of the wind project lifecycle (excluding the actual manufacturing of the wind turbine), which have been introduced in Figure 11. The risk framework model were constructed based on the initial literature review and the feedback from employees from a wind turbine manufacturer, universities, wind project developers, anti-wind organizations, and politicians all part of the wind industry in the targeted countries. The 10 risk parameters have formed the basis of the research methods applied in this study

and are expected to cover all of the risks that an onshore wind project in Northern European forested areas can face.

Figure 11 Risk framework model

Construction risks	Explanation of assumed risks	Operating risks	Explanation of assumed risks	Decommissioning risks	Explanation of assumed risks
Site and resource assessment	• Improper assessments • Insufficient knowledge of roughness effects in forests • Outdated software and calculation methods	**Performance**	• Lower-than-estimated production • Errors • Increased maintenance needs	**Repowering**	• Greater need for redoing the construction work
Social opposition	Complaints leading to delays due to the: • Environmental impact • Physical impact on humans • Socioeconomic impact	**Environmental degradation**	• Impact on birds and bats • Noise and visual interference	**Recycling and waste**	• Dismantling requires transport and space • Inaccurate waste impact estimates
Delays	• Social opposition • Environmental studies	**Return on investment**	• Unpredictable wind conditions result in worse investments than expected		
Cost overrun	• Road construction in forests • Felling of trees • Cabling				
Land use	• Felling of trees • Protected areas • Impact on wildlife leading to social opposition				
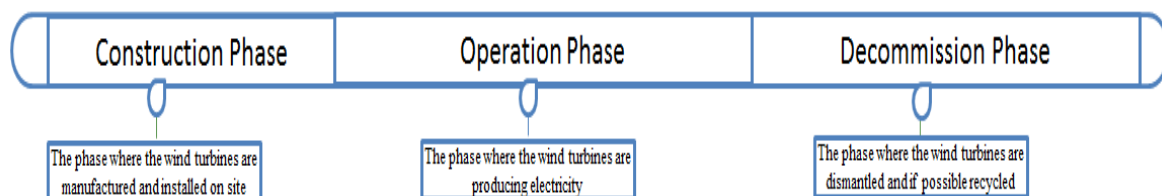
The remaining part of the research paper is structured according to the three phases of the wind project lifecycle, where the literature covering each risk parameter is presented and analyzed.

2.2.2.2   Literature review

This study applies a similar literature search strategy as Sovacool and Brossmann (2010), as an initial broad search for literature has been conducted following specific search words, hereafter another search round were established including the word "Forest", which filtered away a large portion of irrelevant papers from the original search. This approach were similar to the search method applied by Sovacool and Brossmann (2010), yet, it differs in the sense that Sovacool and Brossmann (2010) also took popular articles into consideration and were targeting papers on hydrogen economy. In this research, the comprehensive literature study has been carried out to discover the risks when deploying wind turbines in forested areas. A search through peer-reviewed journals using the online databases; ScienceDirect and Google Scholar revealed a large number of previous studies. The review were conducted using the following keywords in the original search: "Risk," "Wind Turbines," "Wind Power," "Siting," and "Wind Energy," in an "And" combination with "Forest," "Denmark," "Sweden," "Norway," "England," "Northern Ireland," "Northern Europe," "Nordic," "Europe," "Wales," "Scotland," or "United Kingdom," and the 10 risk parameters presented in Figure 11. The search for literature ended in July, 2015, and a total of 242 academic papers were identified, after which a filtering process was conducted, excluding irrelevant papers with little or no focus on the topic, as described above. The final result was 102 papers covering the 10 risk categories, which formed the basis for the most comprehensive review of onshore wind energy in Northern European forested areas. The outcome of the 102 papers is presented in Figure 12, providing the reader with an overview of the coverage of the various risk categories associated with onshore wind turbines in forested areas in Northern Europe and each phase in the wind turbine lifecycle.

Figure 12 Academic papers divided into risk parameters and lifecycle phases
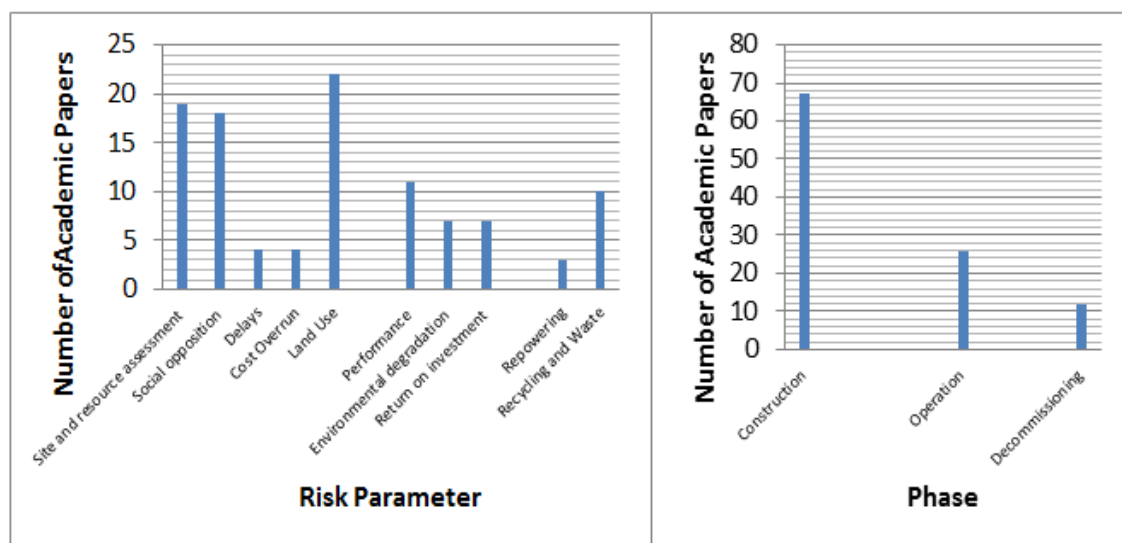
The most debated lifecycle phase and risk category regarding wind turbines in forested areas in Northern Europe was revealed as the *Construction Phase* and *Land Use*, yet some of the papers in the *Land Use* category could easily have been grouped together with *Social Opposition*. The fact that the construction phase is the most academically analyzed phase of a wind turbine lifecycle hardly comes as any surprise, since the remaining risks depend on the risk categories in this particular phase. Another detail of the result from the literature search, which might impact the overall results are the risk of including papers that only mentions "forests" without actually studying the impact of wind power in forests. Consequently, this would impact the research in a negative way, as the study then would be based on risks for onshore wind turbines not necessarily deployed in forested areas.

An analysis has been carried out revealing the number of publications targeting each of the countries in this study.

Figure 13 Country division of published literature
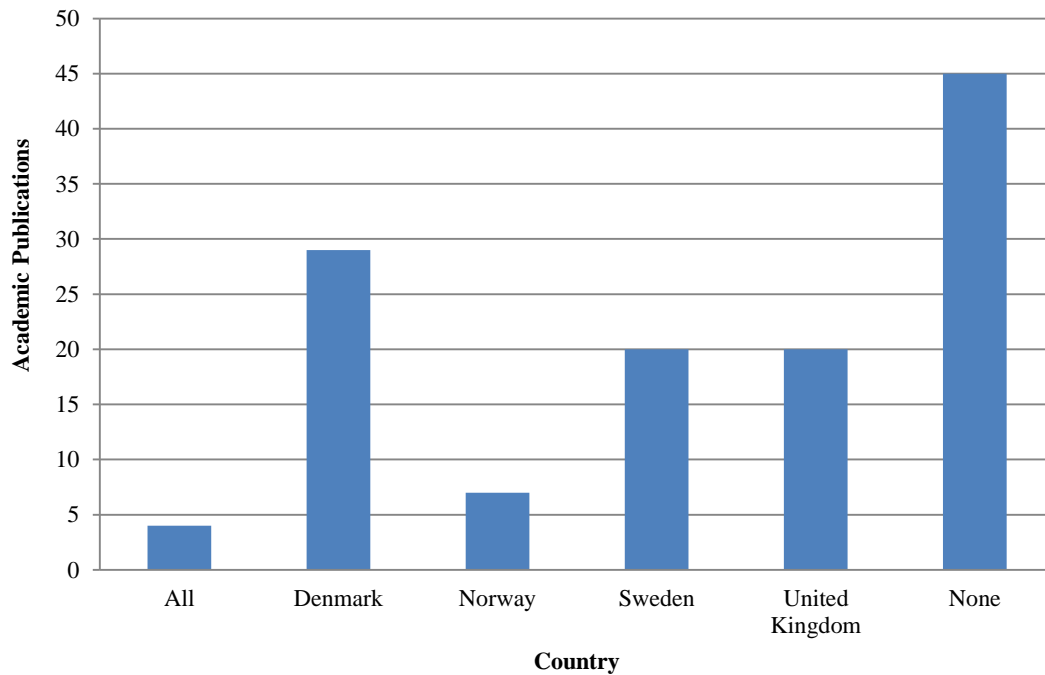
The results presented in Figure 13 indicate a clear overweight in terms of the literature contribution from Denmark and *None*. *None* refers to general studies without a target country, such as "Europe," studies not focusing on any geographical risks, or studies referring to a country other than those referred to in this research. The studies not directly targeted on the implied countries have been included, as it is believed that some of the risk parameters can be applied across borders. *All* have been used for publications focusing on all of the countries in this study.

2.2.2.3 Case selection

Figure 14 highlights the implied countries in this study. The argument for targeting these countries is being explained in the following.

Figure 14 The targeted countries (Denmark, Norway, Sweden, and the UK)

69

The wind conditions in the targeted countries are considered some of the best for wind energy production (Wizelius, 2007; Troen & Petersen, 1989), and the market acceptance level (Sovacool & Ratan, 2012) favors the wind industry (Strachan et al, 2006). Denmark is covered by 13.5% forest (Skov & Landskab, 2010), Sweden 66% (Swedish Forest Agency, 2014), Norway 38% (Nordic Forestry, 2009), and the UK 12% (Forestry Comission, 2014). As presented in Table 11, the uniqueness parameters of the targeted countries are based on the domination of coniferous tree types, and additionally a similar wind regime with a prevailing wind direction from south-west. Such specifications could also have been discovered for other countries in the world, yet, these countries represent the mature and developing markets, see Figure 2 and 3.

Table 11 Northern European forest facts

Country	Installed wind capacity (MW), late 2014 (EWEA, 2015)	Percentage of country covered by forest	The dominating tree types	References
Denmark	5,376	13.5%	Abies alba and Picea abies 40.4%	(Skov & Landskab, 2010)
			Deciduous Trees 39.5%	
Norway	819	38%	Picea abies 47%	(Swedish Forest Agency, 2014)
			Pinus sylvestris 33%	
Sweden	5,424	66%	Picea abies 42%	(Nordic Forestry, 2009)
			Pinus sylvestris 39%	
UK	12,440	12%	Picea sitchensis 29%	(Forestry Comission, 2014)
			Pinus sylvestris 17%	
			Deciduous Trees 40.2%	

The intention of this study is to review the risks associated with wind turbines in forested areas through a comprehensive targeted literature study as summarized in a risk framework model for further application in the wind industry.

2.2.3   Construction risk parameters

As Figure 11 above indicates, the five construction risk parameters relate to the risks that need to be considered in the period before the wind turbines are in operation. These parameters are vital for the later performance and return on the investment in the wind turbine and even the political and public approval of the wind project.

2.2.3.1   *Site and resource assessment*

A common understanding of wind turbines in forests defines the gravest risk to be the uncertainties in site and resource assessments, as the impact of the trees remains an unpredictable factor. The main root error can be attributed to the unpredictable wind conditions (Bergström, et al., 2013; Arnqvist, 2013; Dellwik, et al., 2014). The wind speed usually varies, following (3)

(3)
$$\frac{U(z1)}{U(z2)} = \left(\frac{z1}{z2}\right)^{\rho}$$

where U(z1) and U(z2) define the wind speeds at heights z1 and z2, and p is the power law exponent (Sahin, 2004; Manwell, 2009). The wind speed in the forest is acting differently, however, as the wind profile mixes exponentially from inside the forest to logarithmically above the forest (Bergström, et al., 2013). There are numerous issues when being unable to determine the wind speed, beyond undefined loads on the wind turbine, the energy output will vary a lot from what has been estimated. As a rule of thumb, the power in the wind is proportional to the third power of the wind speed (Manwell, 2009), meaning that a wind turbine will produce 80% less energy at 6 m/s as compared to 8 m/s, and a miscalculation in the resource assessment can result in a misleading business case. This section therefore seeks to describe and divide the risks associated with the site and resource assessments in forested areas.

Changes in the layers surrounding the forest
The impact of forests on wind conditions can be understood by defining the changes of wind speed in the wind layers in, around, and above the forest, as illustrated in Figure 15.

Figure 15 The forest's impact on wind speed (Gardiner, 2004)
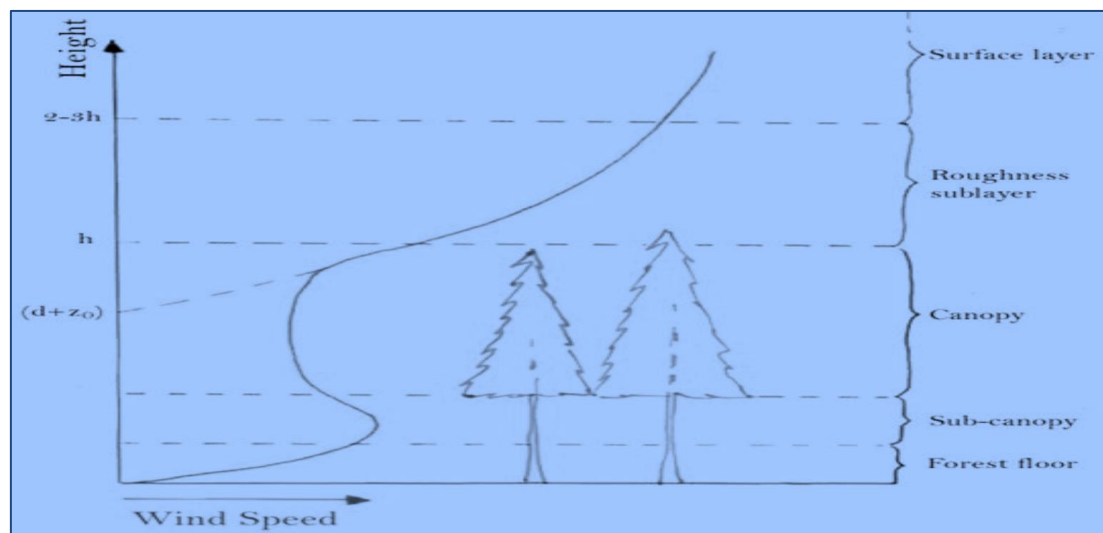
The size of the boundary layer varies between 100 meters and 2 kilometers. The lowest 10% is referred to as the "surface layer," where the air and wind flows are in direct contact with the ground. The topography of the surface impacts the beginning of the surface layer. With low vegetation and small obstacles, the surface layer starts at ground level (z0); above forests, however, the surface layer begins at a higher height, at a distance d, which is referred to in wind simulation terms as the displacement height (Junge & Westerhellweg, 2004). Another layer within the surface layer is the roughness sublayer. In forested areas, this layer cannot be compared to a normal roughness layer above low vegetation due to the impact of the forest. This is where the wind profile shifts from exponentially within the forest to logarithmically above the forest, and this change in the wind profile causes turbulence and unpredictable wind flows. It is worth mentioning that the turbulence and changes in wind speed above the forest canopy vary on the impact from the atmospheric stratification (Brayshaw, et al., 2011).

71

The impact of different forest formations

Bergström et al. (2013) presented a study based on a range of measurements which revealed the impact of heterogeneous forests. The result was that the roughness impact from a heterogeneous forest with a lot of clearings will be higher than that from a homogenous, dense forest. It has also been proven that the forest formation has a varying impact on the wind conditions, depending on the point of measurement being at the edge or in the middle of the forest (Dellwik, et al., 2014; Boudreault, et al., 2014), and that clearings inside a forest have a major impact on the wind speed and turbulence intensity (Bergström, et al., 2013; Frank & Ruck, 2008). Different forest formations and tree types also have an impact on the roughness length. The academic literature seems to disagree on the roughness length for different tree types (Hui & Crockford, 2008). The amount of literature on this particular subject indicates the uncertainty of—yet need for—defining more precise roughness lengths for the tree types in Northern Europe. The importance of the roughness length can be defined by presenting the importance according to the velocity profile. As already mentioned, the velocity profile of the wind becomes logarithmic above the forest company, and following

(4)
$$V = (\frac{u}{k}) \times \ln(\frac{z-d}{z_0})$$

where k determines the von Karman constant and u the friction velocity, z defines the height, d defines the zero-plane displacement height, and z_0 the roughness length, meaning that a change or incorrect estimation of these parameters can result in a different estimated wind speed and therefore a wrong estimated energy production.

The uncertainty of computer simulation programs

Raftery et al. (2004) discussed five different models for wind shear over forests, concluding that none were adequate and that local measurements were needed for positioning wind turbines in forests. One of the reasons could be that the wind direction can change above the forest; a theoretical measurement gives a wind veer of 90 degrees between the forest floor and boundary layer top and 60 degrees between the ground and 250 m. According to Bergström et al (2013), this is considered much higher than what is predicted by industry simulation programs. In addition to the study by Raftery et al. (2004), Hui and Crockford (2008) discovered that the settings applied in some of the widely used commercial software programs can vary considerably, thereby concluding that the software programs are capable of estimating the impact of the forest; it just comes down to too many options misleading the user.

2.2.3.2 Social opposition

Social opposition, even merely a lack of social acceptance, poses a great danger to the development of wind projects, often resulting from different incentives and pressures (Read, et al., 2013). Devine-Wright (2005) found that social opposition is a risk worthy to consider in the construction phase, as the social acceptance of the wind project constantly declines until the moment where the wind turbines actually come into operation. Hereafter, the social acceptance starts inclining (Devine-Wright, 2005). A recent study by Enevoldsen and Sovacool (2016) presented synthetic reasons for social opposition to wind farms, which have been summarized in Table 12 and analyzed subsequently to determine if the same reasons for opposition apply to forested areas in the targeted countries.

Table 12 Synthetic reasons for social opposition to wind farms (Enevoldsen & Sovacool, 2016)

Dimension	Component(s)	References
Environmental impact	Flora and fauna	(Saidur, et al., 2011)
	Reduction of wildlife	(Magoha, 2002; Bright, et al., 2008; Chiras, et al., 2009)
	Felling of trees	(Devine-Wright, 2005)
Visual Impact	Size, color and shape of the wind turbine	(Roques, et al., 2010; IEA, 2010)
	Number of wind turbines	(Wizelius, 2007)
	Noise and flicker effects	(Manwell, et al., 2009)
	Usage of landscape	(Jobert, et al., 2007)
	Involvement in location	(Nadaï & Labussière, 2009)
Socioeconomic Impact	Tourism	(Jobert, et al., 2007; Ladenburg & Dubgaard, 2007)
	Property and land values	(Jobert, et al., 2007)
	Local benefits	(Nadaï & Labussière, 2009)
	Lack of information	(Nadaï & Labussière, 2009)
	Political and market acceptance	(Roques, et al., 2010; Sovacool & Ratan, 2012)
	Number of wind projects in the area	(Jobert, et al., 2007)

Social acceptance in Denmark

Surveys reveal that most Europeans support wind energy (Saidur, et al., 2011). Previous studies have defined the social acceptance of wind turbines or lack thereof in each of the targeted countries. In Denmark, over 100,000 private citizens have personally invested in wind turbines (Saidur, et al., 2011), and this tradition concerning private ownership is expected to have contributed to the high level of social acceptance of wind power (Ek, 2005). Moreover, there has been political support for wind turbines in Denmark since the oil crises in the 1970s, and the favorable feed-in tariffs in the 1990s encouraged a massive increase in wind turbine installations and the wind industry in general (Ek, 2005; Ek, et al., 2013). The recent trends in Denmark also focus on the development of new, large-scale wind farms (Ek, et al., 2013; Sperling, et al., 2010), which may influence the public perceptions of wind energy.

Social acceptance in Sweden

Khan (2003) discovered that the development of Swedish wind projects is based just as much on the public acceptance of wind power in the local communities as the wind conditions. However, this can be closely related to the more recent political support for wind power in Sweden. Like Denmark, Sweden experienced oil crises in the 1970s; unlike Denmark, however, this resulted in investments in nuclear power, and the Swedish development of wind projects was very slow until the 2000s (IEA, 2013). From 2005–2010, Swedish wind power production increased dramatically from 0.94 to 3.51 TWh (Ek, et al., 2013). This increase can partly be attributed to the government establishing national interest areas for wind power in 2004 and extending the renewable electricity certificate system from 2010 to 2035, which secured investments (Pettersson & Söderholm, 2009). Moreover, the

municipality with the highest installed wind capacity is Malmö (Ek, et al., 2013), which is one of the most densely populated areas in Sweden and has a history of major nuclear power plant investments. Despite this increase in wind power in Sweden, researchers point out how the decentralized Swedish system often contributes to local opposition to wind projects (Ek & Persson, 2014). In Sweden, the local community must approve wind projects (Pettersson, 2008; Pettersson, et al., 2010), and, unlike Denmark, the municipality does not have to allocate areas for wind projects. A survey conducted in 2002 revealed that 28% of all Swedes have negative attitudes to wind power (Pedersen & Persson, 2004). This number is expected to fall, as Ek et al. (2013) found that municipalities with installed wind power were more likely to support wind power, and given the development of wind capacity in Sweden, a lower percentage of negative responses can be expected in the future. Those who oppose wind projects in Sweden are often older and have a high income (Ek, 2005) (Söderholm, et al., 2007). People do not generally complain about the visual and noise impact of wind turbines (the NIMBY parameters (Hellström, 1998; Ek, et al., 2013), and the opposition to turbines is strongest to those positioned in the landscape, as surveys have revealed the strongest opposition against wind turbines positioned on mountains and in forests (Söderholm, et al., 2007), and the Swedes would even prefer higher energy costs to having wind turbines located in such areas (Ek & Persson, 2014).

Social acceptance in Norway

Completely opposite the Danish case, where there has been decades of political support for wind energy leading to a growing wind industry, Norway experienced neither political support nor rapid growth in the wind industry over the course of the 1990s and 2000s, which, combined with the large national oil industry, could be why studies have found that the public support and acceptance of wind power is too low to motivate the expansion of the wind industry in Norway (Pettersson, et al., 2010).

Social acceptance in the UK

The UK has become one of the countries with the most installed wind turbines with respect to both onshore and offshore turbines. On the national level, large offshore wind farms have been recently established, avoiding many of the risks associated with the lack of social acceptance, which supports the inverse NIMBY public perceptions discovered by Warren et al. (2005). Warren and McFadyen (2010) showed how the local public ownership of wind turbines reduces the risk of complaints and social opposition. With the increase in wind turbine size and increase in the number of wind turbines grouped together in a single project, however, an increase in rejected onshore wind projects has been experienced in the UK, which verifies the account of social opposition presented in Table 12. Enevoldsen and Sovacool (2016) suggested that negative attitudes towards wind projects can be reduced by involving locals in the decision-making processes. This is especially important in Sweden due to the public enquiry round held in the end of the planning of Swedish wind projects, which allows local residents to block wind projects. Furthermore, Pettersson et al. (2010) revealed that the Danish acceptance process for wind projects, which is somewhat comparable to the British process, yet, the environmental demands for British wind farms recently been criticized (Phillips, 2015; Phylip-Jones & Fischer, 2015), relies on measureable parameters, such as noise emissions and flicker effect, whereas the legislation is more vague in Sweden and Norway (Pettersson, 2008; Söderholm, et al., 2007). Further along these lines, Pettersson et al. (2010) found that the average development time for wind projects is higher in Sweden (ca. 5 years) than in the UK, Denmark and Norway (2–4 years). The average development time for European wind projects varies between 1.5–4.5 years (Neuhoff, 2005).

Few studies does address the specific risks concerned to wind projects in forested areas in Northern Europe, whereas forest more has been treated as one of many parameters in such studies.

Nevertheless, it becomes clear that social opposition threatens onshore wind energy in forested areas in Northern Europe, as all of the risk factors presented in Table 3 are present in the targeted countries and, besides the physical impact on humans, are likely to increase in forested areas. Therefore, future studies needs to target and address the risk of social opposition in forest only.

2.2.3.3 *Project Delays*

As in all construction projects, delays are a risk worth mentioning. Wind projects in forested areas can be delayed by a range of events, some predictable and others less so. Table 13 categorizes the outcome of the literature review on the events causing delays in forest wind projects. More generalized reasons for delays, such as uncertain project management (Odeh & Battaineh, 2002), have not been included in the Table.

Table 13 Factors leading to delays

Factors impacting delay	Reasons	Most likely to experience in	Reference
Policy	Vague definitions of "wind farms" condition what can be questioned during the development period	Sweden	(Söderholm, et al., 2007)
	The public enquiry round in the end	Sweden	(Ek, et al., 2013; Pettersson, 2008)
Site-specific	Due to the low temperatures in Northern European forests, icing can occur and extend the measurement period	Norway and Sweden	(Arnqvist, 2013; Cattin, 2012)
	Wildlife species living near the proposed wind farm can require additional environmental studies	UK, Denmark, Norway, and Sweden	(Nadaï & Labussière, 2009)
Social	Opposition due to visual and noise impact	UK, Denmark, and Norway	(Betakova, et al., 2015; Ladenburg & Dubgaard, 2007; Warren, et al., 2005; Jones & Eiser, 2010)
	Opposition due to landscape interference	Sweden	(Ek, 2005; Ek & Persson, 2014; Söderholm, et al., 2007)

2.2.3.4 *Cost overrun*

Cost overrun presents an interesting risk parameter for the construction risks yet a rather novel risk parameter, as reflected in the low number of peer-reviewed studies published on this topic (see Figure 12). Nevertheless, Sovacool et al. (2014) investigated 35 wind farms to test the potential cost overrun aspects for wind power projects. The outcome was a mean cost escalation of 8%. Furthermore, the study revealed that a longer time period equals a cost overrun, which is entirely unrelated to the size of the project in question, yet no conclusions could be drawn on forest projects. However, it is possible to conclude that if the delays presented in Table 13 occur, they will most likely include cost

overruns, despite the rapid innovations in the wind industry (Sovacool & Enevoldsen, 2015). Even though wind power has been found to be one of the electricity infrastructures with the lowest cost overrun (Sovacool, et al., 2014), the risks can be assumed to be greater for onshore wind projects in forested areas due to the fact that onshore projects in forested areas are often accompanied by higher development costs than other onshore projects in the construction phase, primarily due to the felling of trees, road construction, and greater distances for grid connection; nevertheless, no studies have targeted the cost overrun in forest wind projects.

2.2.3.5 *Land use*

The risk related to land use is associated with social opposition and social values in many of the existing studies. Having already described the risks associated with social opposition and land use, this section focuses on other parameters, all of which are related to the installation of wind turbines in forests (Christie & Bradley, 2012). The installation of wind turbines raises risks related to the local bio system (Dai, et al., 2015). For wind turbines in forested areas, this may include road construction and deforestation (Dai, et al., 2015). Such necessary activity might have bearing on the commercial viability of a project if too many trees are to be felled (Perks, et al., 2010). Based on the literature review, it is possible to conclude that the land use risks can be divided into four factors, as presented in Table 14.

Table 14 Risk factors associated to wind turbines in forested areas

Factor	Risk	Reference
Market	Land use based on forestry	(Santos-Alamillos, et al., 2015)
	Land use based on farming	(Santos-Alamillos, et al., 2015)
Policy	Restrictive areas	(Siyal, et al., 2015; Möller, 2006)
	Changes in energy policy	(Pettersson & Söderholm, 2009)
	Approval of and enquiries regarding wind projects	(Pettersson & Söderholm, 2009; Söderholm, et al., 2007)
Social	See Table 13	
Site-specific	Changes in tree types and forest formations make it difficult to estimate the wind flow	(Bergström, et al., 2013; Arnqvist, 2013; Dellwik, et al., 2014)
	Previous public usage of area	(Nadaï & van der Horst, 2010)

Siyal et al. (2015) suggested areas for new wind project development based on a map consisting of restricted areas combined with areas with great wind potential, meaning an approach that somehow follows the four factors mentioned above. As Santos-Alamillos et al. (2015) explain, however, the land use constantly changes due to both nature and human interactions. By investigating the carbon emission savings from wind farms, the impact of the felling of trees can be determined as:

(5) $$S = 24 \times 365 \times \frac{\text{pcap}}{100} \times n \times c \times E$$

S is the annual emission savings, pcap the capacity factor, n the number of wind turbines, c the turbine capacity, and E is the emission factors measured as CO_2 MWh-1. For Scottish wind projects, Perks et al. (Perks, et al., 2010) found that a clear-felling of a forest would require 12 years of wind turbine operation to repay the carbon payback. It can be concluded that specific risks do exist for onshore wind energy in the forested areas in Northern Europe.

2.2.4   Operation risks

The operation risks mainly relate to the performance of the wind turbines in forested areas. Furthermore, the intention was to investigate if environmental degradation risks were more severe for onshore wind projects in forests than for projects located outside of forests, but the literature provides no clear answer to this question.

2.2.4.1   Performance

The first risk parameter in the operation phase is a continuation of the first risk in the construction phase—the site and resource assessment—as conclusions regarding performance are closely related to the predicted performance (Girard, et al., 2013). As determined earlier in this research, trees pose obstacles that cause changes in the local wind conditions (Lopes da Costa, et al., 2006). This can be measured in terms of the turbulence intensity

$$(6) \qquad\qquad\qquad\qquad\qquad Ti = u'/V$$

This indicates the changes in the wind speed, u' being the root mean square of the turbulent velocity fluctuations and V being the average wind speed. With high turbulence intensity, wind turbines risk fatigue loads and vibration errors beyond the capacity of the wind rotor and blades (Nadaï & van der Horst, 2010). The literature presents numerous reasons for errors (Hameed, et al., 2009) and methods to detect and avoid these errors to optimize performance (Lopes da Costa, et al., 2006; Márquez, et al., 2012; Tian, et al., 2011). However, none of the studies specifically address the performance of wind turbines in Northern European forests.

2.2.4.2   Environmental degradation

Having already described the land use risks in the construction phase, this section focuses on the environmental risks from operating a wind turbine, which have been widely recognized in the literature in terms of the physical impact on humans and animals.

Impact on humans

The noise and shadow effect caused by wind turbines is one of the main reasons for complaints in the public enquiries (Nadaii, 2007). The sound level of wind turbines is measured in dBA (decibel A), which measures the sound the ear is capable of hearing (Wizelius, 2007). Basically, a wind turbine produces two types of noise:

Aerodynamic noise: This is the type of noise created by the wing cutting through the air. People can only hear this noise when they are very close to the wind turbine.

Mechanical noise: This is the type of noise created by the gears and other moving parts within the turbine. Soundproofing can reduce the mechanical noise.

Forested areas can be considered rural, which explains why there is a minimal physical impact on people.

Avian and chiropteran mortality

A range of studies have been conducted addressing the impact of onshore wind turbines on birds and bats (Leung & Yang, 2012; Magoha, 2002; Dai, et al., 2015; Peste, et al., 2015). Zhang (2008) states that birds are one of the largest groups of animals experiencing fatal collisions with wind turbines, and a study estimated that wind turbines killed 234,000 birds annually (Loss, et al., 2013). While bats react to moving targets, the mortality of bats also increases around wind turbines (Dai, et al., 2015).

Wind turbines have also been observed to have a negative influence on bird breeding and feeding behavior. However, even though attempts have been made (Bright, et al., 2008), Wang et al. (2015) state that the uncertainty regarding why and how birds are killed must be clarified in order to arrive at a proper conclusion concerning the impact of wind turbines on bird mortality; the same can be said for wind turbines in forested areas.

The felling of trees can be assumed to cause the death of birds and bats (Sovacool, 2009; Müller, et al., 2013), yet it is unimaginable that wind turbines will cause the number of fatalities among birds caused by other energy resources (Sovacool, 2009) and other causes such as cars, cats and cables (Chiras, et al., 2009).

2.2.4.3 *Return on investment*

Besides an expectation of an investment in clean energy (Atlason & Unnthorsson, 2014), wind turbines have become a topic for major investments and how to make the most of investments (Caralis, et al., 2014; Wiser, 1997). An excessive number of academic studies have been carried out on the return on investment and risk management of business cases of onshore wind projects (Atlason & Unnthorsson, 2014). The net present value of a wind turbine is a measure used by investors to rate their investment. The net present value can be calculated using

(7)
$$\text{NPV} = \sum_N CF_n \times (1+r)^{-n}$$

where n defines the numbers of years, CF_n defines the cash flow in the related year, and r is the discount rate (Gass, et al., 2011). When combining the net present value with the internal rate of return, the investor knows the risk allowed in the project. Yet even though the capital cost of a wind project can be estimated to be around 75% of the combined cost (Boomsma, et al., 2012), many factors must be considered, including the electricity market (Hasani-Marzooni & Hamid Hosseini, 2011), local financial support structures for renewable energy (Morthorst, 1999), the uncertainty of financial support structures (Barradale, 2010), and of course most importantly the work conducted in the siting and resource assessment stage. None of the literature targeted in this study explicitly focuses on wind projects in forested areas, but it can be estimated that the increased risks in the construction phase possibly lead to a different investment scenario than the one for other onshore wind projects in Northern Europe.

2.2.5 Decommissioning risks

The decommissioning risks relate to the phase after the production lifetime of the wind turbine. Due to large multi-megawatt wind turbines being a novel technology with an average lifetime of 20–25 years, the industry has yet to experience large numbers of these turbines reaching this phase of the lifecycle; nevertheless, researchers have tried to estimate the opportunities and challenges that the industry will face.

2.2.5.1 *Repowering*

Del Río et al. (2011) define repowering as the process by which existing wind turbines are replaced with new wind turbines with a higher energy output. Given that wind turbines have an average lifetime of 20–25 years and, as mentioned above, it is difficult to obtain land for wind turbines for numerous reasons, repowering can avoid some of the risks and investment costs that were previously encountered in the construction phase (del Río, 2011); the land has already been acquired, the grid connection has already been established, and the public has grown accustomed to living with a wind farm. Most importantly, decades of wind data ought to reduce the risks regarding wind conditions

dramatically. It is worth mentioning that new environmental studies must be carried out, and the political support for wind energy may have changed (del Río, 2011). Denmark, a country that can be considered a repowering pioneer, had repowered approximately 66% of the old fleet of wind turbines by December 2005 (del Río, 2011), and the other global wind energy pioneers are currently doing the same (Goyal, 2010; Rader, 2007). While this risk parameter has not been covered by the literature, it can be expected to be a future topic, as repowering in forested areas can be expected to reduce the construction risks.

2.2.5.2 *Recycling and waste*

According to Zhang (2008), a wind turbine produces enough clean energy within a few months to cover the energy used to manufacture and transport it. Furthermore, a range of lifecycle analyses of wind turbines focusing on the environmental externalities in terms of emissions in the manufacturing phase (Crawford, 2009; Tremeac & Meunier, 2009; Martínez, et al., 2009; Guezuragaa, et al., 2012; Arvesen, et al., 2009; Schleisner, 2000) have produced different outcomes. However, few, if any, studies have adequately investigated the environmental externalities caused by wind turbines in the decommissioning phase; this despite the increasing need for the wind industry to consider solutions for the bulky waste resulting from decommissioned wind turbines. For example, Andersen et al. (2007) predicted that as of 2040, 380,000 tons of fiber composites from wind turbines will have to be disposed annually, and the wind turbine blades in particular appear to pose a problem for recycling (Albers, et al., 2009; Lenzen & Munksgaard, 2002). Based on these studies, it was found that 37% of the rotor and blades, 90% of the tower and 87% of the nacelle can be recycled due to the high percentage of the wind turbines consisting of metals.

The literature review in this study has not revealed whether there are special circumstances for onshore wind turbines in forested areas in Northern Europe; nevertheless, by applying the findings from the two risk categories Cost Overrun and Land Use, we know that the waste must be transported over longer distances than the general onshore wind project.

2.2.6 Discussion and comparative analysis

This section discusses the results from the literature search in order to determine if certain patterns can be discovered in the development of installed wind capacity compared to the publications of academic literature and the development of various risk parameters. The investigation has addressed whether there is a correlation between the installed wind capacity in the targeted countries and the development of publications of risk parameters. Figure 16 presents the development in installed wind capacity in the targeted countries and Figure 17 the development of literature targeting each of the countries under investigation here.

2.2.6.1 *Comparative analysis of literature*

A clear correlation is revealed between the development of installed wind capacity and publications on the risks for onshore wind power in each of the countries in question. Denmark has a lengthy history with wind power (Roques, et al., 2010) and has been the leading country for case studies in the period 1994–2010, while a dramatic increase in the installed wind capacity in the UK during the period 2007–2015 has led to an increase in British publications; the same goes for Sweden in the period 2009–2015 and more recently for Norway.

Figure 16 Installed wind capacity in the targeted countries (EWEA, 2016)
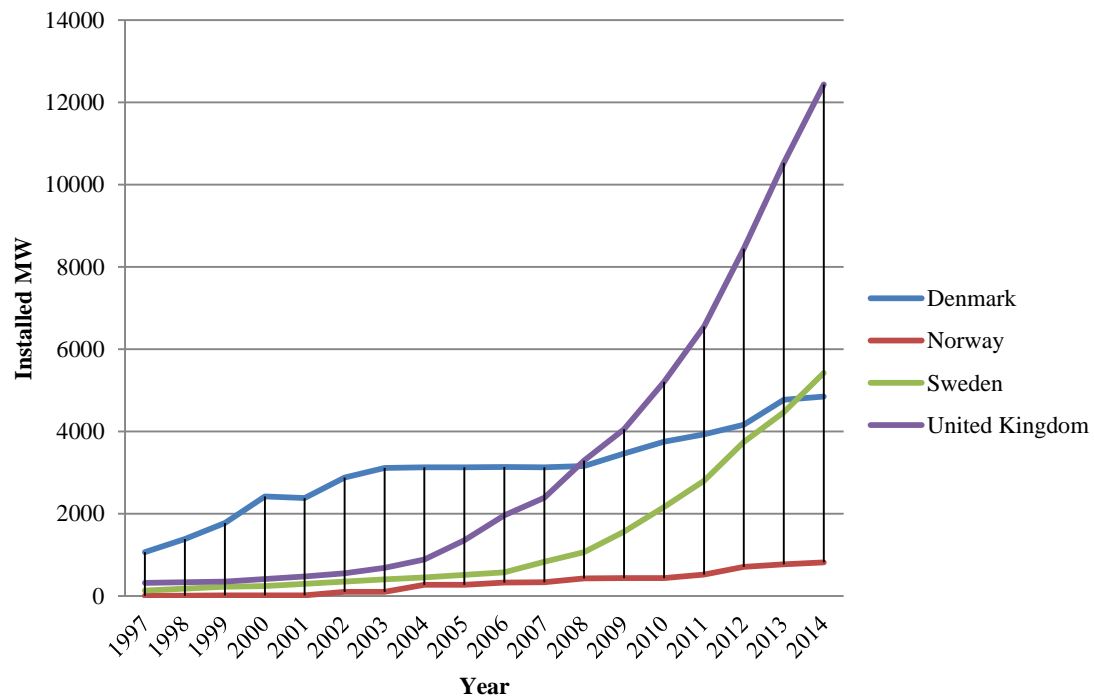
Figure 16 presents the development of installed wind capacity in each of the targeted countries, whereas Figure 17 presents the development of publications related to each of the countries.

Figure 17 The development of publications for each of the countries
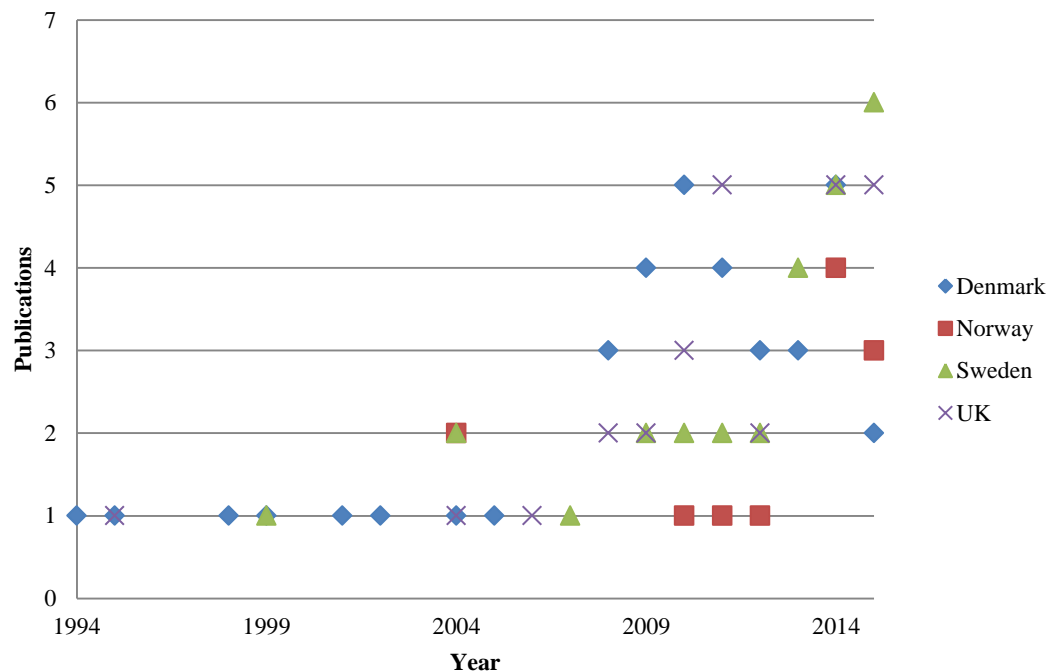
When analyzing the literature coverage as in the methods section of this study, a natural source of error is that some topics produced more "search hits" than others; however, this only reveals which

parameters have been considered to be the most "risky" by the academic literature, for which reason Figure 18 reveals the development of studies addressing each risk parameter.

2.2.6.2 Temporal phases and trends

Besides indicating a clear increase in the academic study of the topics relating to the risks involved in onshore wind projects, it is also possible to conclude that the number of studies focusing on Land Use, Social Opposition, Environmental Degradation and Performance is increasing. It can be discussed whether the keywords apply to studies within these risk parameters.

Figure 18 The development of published literature
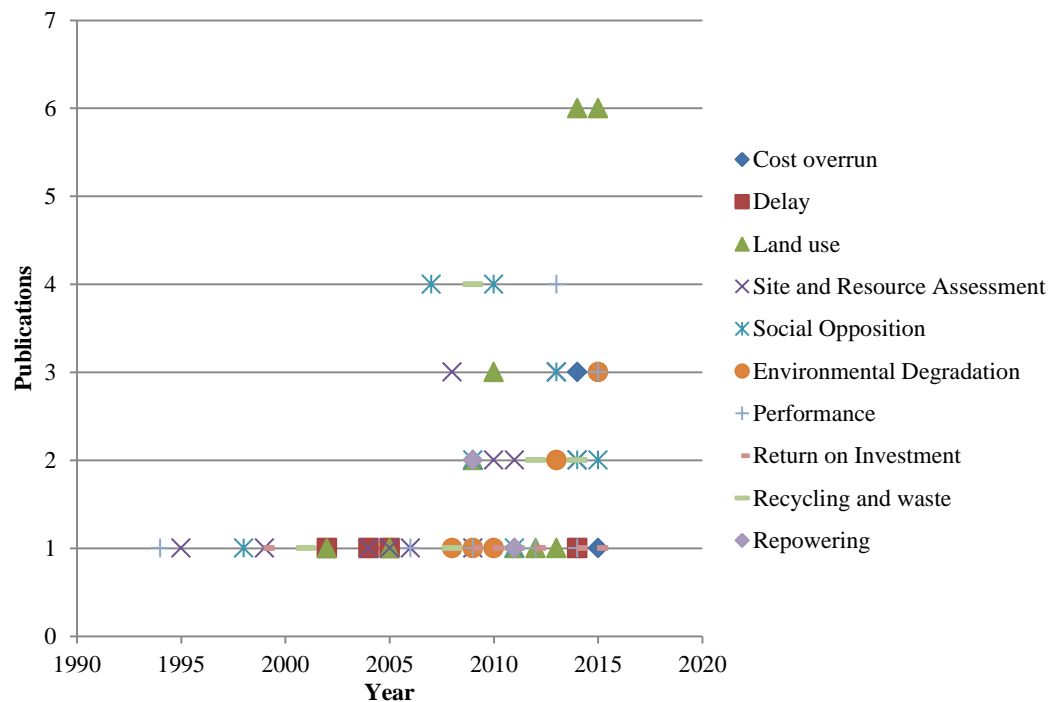
When investigating the occurrence of risk parameters it becomes clear that in first phase from the mid to late 1990s, it is most about site and resource assessment. This can be explained due to the nascent stage of wind energy in Denmark, why it was critical to investigate how to develop the most efficient wind projects. The academic contribution of social opposition can be related to explosive growth in wind turbine size from 1995 – 1999, where the height of the largest wind turbines were doubled.

The second phase, from 2000-2010, presents a rapid growth in academic contributions, which of course can be related to wind energy installations in Sweden and in particular in the UK. Site and resource assessment is still an important topic around 2005, possible due to the boom in installed wind energy in the UK. New risk parameters are presented in this phase, as land use, environmental degradation, delay and repowering becomes an important topic. The first three risk parameters are most likely to contribute to the growing amount of studies on social opposition.

The final phase presented in this study, from 2010-2015, presents an explosion in studies related to land use, social opposition, cost overrun and environmental degradation. Statistics regarding developed wind farms in the targeted countries reveals larger wind farms with larger wind turbines. Combined with less publications and installed wind capacity related to Denmark, a country where the public are supportive of wind energy, the increase in size of wind farms could be the reason for the

increasing concentration on land use and related topics, as wind farms suddenly removes nature instead of becoming a part of the landscape.

2.2.6.3   *Future research*

Having presented the most comprehensive literature study conducted on onshore wind energy in forested areas in Northern Europe, it can be concluded which of the 10 risk parameters that have been covered sufficiently and which have not. The division is merely based on the author's analysis of this paper and search results and categorized using "X" for parameters that have been covered, "–" for parameters with some coverage of wind turbine risks associated with Northern European forests and "O" for parameters which are only covering onshore wind projects in general.

Table 15 Evaluation of the academic contribution

Construction risks	Covered by the literature	Operation risks	Covered by the literature	Decommissioning risks	Covered by the literature
Site and resource assessment	X	Performance	O	Repowering	O
Social opposition	–	Environmental degradation	–	Recycling and Waste	O
Delays	–	Return on investment	O		
Cost overrun	O				
Land use	X				

Only two of the 10 risk parameters have been covered, and even for these two, more specific studies must be carried out. For the remaining risk parameters, further studies must be conducted on the risks for onshore wind power in forests. It is suggested for future practical studies to investigate the lacking constructing risks as soon as possible, as these factors impacts the later risks in the operation and decommission phase of a wind project. Studies can be carried out using data from operating wind turbines, where essential project management parameters such as time planning and construction budget will reveal two of the lacking factors in the construction phase, and add information to the return on investment. The forest agencies of the targeted countries does all have public available databases, from where it is possible to draw conclusions on the amount of forests that has been felled for each wind project, which could reveal the potential risk of land use. For a deeper investigation of the environmental impact, detailed studies on impact on animal and plant life would have to be conducted, maybe even for the entire period of a wind turbine. This challenge is generic for the risks in the operation and decommission phase, as most of the risk factors require experience, measurements and thereby knowledge from the entire wind turbine life cycle, which usually would last up to 20-25 years.

One can argue that for future reviews on broad topics like this one, the keywords applied in the literature search should be even more detailed and targeted than what has been applied in this study, in order to have a scope even further in on wind projects in forests. However, the excessive number of studies discovered on each of the risk parameters indicates that these are risks to be considered for onshore wind projects. It is also a fact that wind project development in forested areas in Northern Europe is a novel innovation and it is therefore to be expected that there is less academic coverage of the risks in the operation and decommissioning phases.

2.2.7   Conclusion

This study has explored the risks associated with onshore wind energy in forested areas in Northern Europe by applying the most comprehensive literature study on wind energy's risks in forested areas. The approach for the literature study and the overall research have been designed by a strategic risk framework consisting of 10 different risk parameters divided into 3 phases of a wind project life cycle. The outcome of the study is an overview of the risks for each of the targeted countries, which have been analyzed regarding its relation to the latest trends in academic literature. This revealed clear patterns and it can be concluded that trends in the literature implies that the community and wind industry shifts in what regard as important.

This study contributes to the wind industry by informing about the risks one has to consider before developing wind projects in forested areas. Furthermore, Table 15 presents that the wind industry still has a lot of risk parameters to consider and explore. Wind energy investors and politicians will learn what risks to be aware of, and further studies based on this research could categorize the importance of each of the ten risk parameters, in order to strategically analyze wind projects in forests. Wind manufacturers and developers will have to pay extra attention to the risks in the operation – and the decommissioning phase, as these have not been covered by recent literature and can be considered novel risks for peer reviewed literature.

This research presents a novel approach to comparative analyses of the relationship between the development of a technology and the development of scholarship. Besides presenting the areas where literature is lacking, scholars in wind energy studies are expected to be able to further develop the strategic risk framework for other geographical areas, for instance to gain knowledge of new markets. Furthermore, it has been learned that risk is complex and multidimensional, why the approach in this research is expected to be applicable for any energy technology. It can be concluded that the current academic contributions regarding the risks associated with onshore wind energy in forested areas in Northern Europe are insufficient, which might define the root cause of wind energy in forested areas; no one has yet completely revealed the risks and uncertainties facing the onshore wind industry in Northern Europe. Perhaps we better understand risk when we encounter such, yet, the contribution in this research aims at avoiding or at least minimizing the risks that can be experienced for wind projects in forests.

2.3 References

The following references were applied in the first journal article.

Adelaja, A., McKeown, C., Calnin, B. & Hailu, Y., 2012. Assessing offshore wind potential. Energy Policy , Volume 42, p. 191–200.

Archer, C. L. & Jacobson, M. Z., 2005. Evaluation of global wind power. Journal Of Geophysical Research, Volume 110.

Arnqvist, J., 2013. Mean Wind and Turbulence Conditions over Forests , Uppsala: Department of Earth Sciences Licentiate Thesis.

Bardach, E., 2011. Practical guide for policy analysis: the eightfold path to more effective problem solving. CQ press.

Bemelmans-Videc, M.-L., Rist, R., Vedung, E. (Eds.), 2003. Carrots, Sticks, and Sermons: Policy Instruments and Their Evaluation. Transaction Publishers, UK.

Bergström, H. et al., 2013. Wind Power in forests, s.l.: Elforsk.

Bilgili, M., Yasar, A. & Simsek, E., 2011. Offshore wind power development in Europe and its comparison with onshore. Renewable and Sustainable Energy Reviews, Volume 15, pp. 905-915.

Blanco, M. I., 2009. The economics of wind energy. Renewable and Sustainable Energy Reviews, 13(6-7), pp. 1372-1382.

CarbonBrief, 2015. http://www.carbonbrief.org/mapped-the-worlds-largest-offshore-windfarms. [Online]
[Accessed 19 January 2016].

Cohen, J., 1988. Things I have learned (so far). American Psychologist, 45(12), pp. 1304-1312.

Cook, T.D., Campbell, D.T., 1979. Quasi-Experimentation: Design & Analysis Issues for Field Settings. Houghton Mifflin Company, Boston, USA.

Dai, K. et al., 2015. Environmental issues associated with wind energy - A review. Renewable Energy, Volume 75 , pp. 911-921.

Dellwik, E., Bingöl, F. & Mann, J., 2014. Flow distortion at a dense forest edge. Quarterly Journal of the Royal Meteorological Society, Volume 140, pp. 676 - 686.

DONG Energy, 2008. Final Report on Offshore Wind Technology. Risoe National Sustainable Energy Laboratory, New Energy Externalities Developments for Sustainability Consortium, pp. 1-60.

Enevoldsen, P, 2016. Onshore wind energy in Northern European forests: Reviewing the risks. Renewable & Sustainable Energy Reviews, Vol. 60, pp. 1251–1262.

Enevoldsen, P. & Sovacool, B. K., 2016. Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France. Renewable & Sustainable Energy Reviews, Vol. 53, pp. 178-184.

EWEA, 2014. Wind energy scenarios for 2020, Brussels: European Wind Energy Association.

Field, A. (2009). Discovering statistics using SPSS. London: Sage.

Gipe, P., 1995. Wind Energy Comes of Age. New York: John Wiley & Sons.

Global Wind Energy Council, 2016. http://www.gwec.net/global-Figures/wind-in-numbers/. [Online] [Accessed 13 January 2016].

Göçmen, T., Laan, P.v.d., Réthoré, P.-E., Diaz, A.P., Larsen, G.C., Ott, S., 2016. Wind turbine wake models developed at the technical university of Denmark: A review. Renewable and Sustainable Energy Reviews 60, 752–769.

IEA, 2008. Renewable Energy Essentials: Wind, Paris: INTERNATIONAL ENERGY AGENCY.

IRENA, 2015. Renewables 2015 Global Status Report, UAE: International Rewneable Energy Agency.

IRENA, 2016. Renewable Energy Capacity Statistics 2016, s.l.: International Renewable Energy Agency.

Koch, C., 2014. The more the better? Investigating performance of the Danish and Swedish offshore wind farm cluster. Journal of Financial management of property construction and real estate, Volume 19, pp. 24-37.

Ladenburg, J., 2009. Attitudes towards offshore wind farms — The role of beach visits on attitude. Energy Policy, Volume 38, pp. 1297-1304.

Lindman, Å., Söderholm, P., 2012. Wind power learning rates: A conceptual review and meta-analysis. Energy Economics 34, 754-761.

Lu, X., McElroy, M.B., Kiviluoma, J., 2009. Global potential for wind-generated electricity. Proceedings of the National Academy of Sciences 106, 10933-10938.

Manwell, J. M. J. &. R. A., 2009. Wind Energy Explained: Theory, Design and Application. 2nd ed. Hoboken: Wiley.

Paulsen, T. & Thüring, H., 2015. Yearbook Wind Energy 2015, Berlin: German Wind Energy Association (BWE).

Perks, M., 2010. Wind Turbines & Trees: maximising net benefit in forestry settings. Aberdeen, APF 2010 – Forestry Commission seminar series..

Perveen, R., Kishor, N. & Mohanty, S. R., 2014. Off-shore wind farm development: Present status and challenges. Renewable and Sustainable Energy Reviews , Volume 29, p. 780–792.

Sahin, A. D., 2004. Progress and recent trends in wind energy. Progress in ENergy and Combustion Science, Volume 30, pp. 501-543.

Son, E., Lee, S., Hwang, B., Lee, S., 2014. Characteristics of turbine spacing in a wind farm using an optimal design process Renewable Energy 65 245-249.

Subramanian, B., Chokani, N., Abhari, R.S., 2015. Experimental analysis o fwakes in a utility scale wind farm. Journal of Wind Engineering and Industrial Aerodynamics 138, 61–68.

Troen, I. & Petersen, E., 1989. European Wind Atlas. Roskilde: Risø National Laboratory .

Valentine, S.V., 2010. Disputed wind directions: Reinvigorating wind power development in Taiwan. Energy for Sustainable Development 14, 22-34.

Valentine, S.V., 2011. Sheltering wind power projects from tempestuous community concerns. Energy for Sustainable Development 15, 109-114.

Valentine, S.V., 2012. Policies for Enhancing Corporate Environmental Management: a Framework and an Applied Example. Business Strategy and the Environment 21, 338-350.

Valentine, S.V., 2014. Wind Power Politics and Policy. Oxford University Press.

Wizelius, T., 2007. Developing Wind Power Projects: Theory and Practice. Earthscan, UK.

WRI, 2010. Fact Sheet: Policy Design for Maximising US Wind Energy Jobs. World Resources Institute (WRI), Washington, DC, USA.

Young, E., 2015. Offshore wind in Europe: Walking the tightrope to success. Ernst & Young Paris.

The following references were applied in the second journal article (Based on the sequential order in the article).

Hills, R., 1994. Power from wind—a history of wind mill technology. Cambridge: *Cambridge University Press.*

Sahin, A. D., 2004. Progess and recent trends in wind energy. *Progress in Energy and Combustion Science ,* Volume 30, p. 501–543.

Bilgili, M., Yasar, A. & Simsek, E., 2010. , . Offshore wind power development in Europe and its comparison with onshore.. *Renewable and Sustainable Energy Reviews,* Volume 15, pp. 905-915.

Manwell, J., McGowan, J. & Rogers, A., 2009. Wind Energy Explained: Theory, Design and Application. Hoboken: *Wiley.*

Christie, D. & Bradley, M., 2012. Optimising land use for wind farms. *Energy for Sustainable Development ,* Volume 16 , p. 471–475.

Szarka, J., 2007. Why is there no wind rush in France?. *European Environment,*Volume 17, pp. 321-333.

Tabassum-Abbasi, Premalatha, M., Abbasi, T. & Abbasi, S., 2014. Wind energy:Increasing deployment, rising environmental concerns. *Renewable and Sustainable Energy Reviews ,* Volume 31, p. 270–288.

Zhang, Z., 2008. Asian energy and environmental policy: promoting growth while preserving the environment. *Energy Policy,*Volume 33, pp. 3905-3924.

Grubb, M. & Meyer, N., 1993. Wind energy, resources, systems and regional strategies. Washington D.C: *Island Press,*

Wizelius, T., 2007. *Developing Wind Power Projects*. London: *Earthscan*.

Leung, D. Y. & Yang, Y., 2012. Wind energy development and its environmental impact: A review. *Renewable and Sustainable Energy Reviews ,* Volume 16 , p. 1031– 1039.

Bergström, H. et al., 2013. Wind power in forests*,* Uppsala.: Elforsk.

Heptonstall, P., Gross, R., Greenacre, P. & Cockerill, T., 2012. The cost of offshore wind :Understanding the past and projecting the future. Energy Policy, Volume 41, pp. 815-821.

Zwaan, B. v. d., Rivera-Tinoco, R., Lensink, S. & Oosterkamp, P. v. d., 2012. Cost reductions for offshore wind power: Exploring the balance between scaling, learning and R&D. Renewable Energy, Volume 41, pp. 389-393.

National Renewable Energy Laboratory, 2005. Assessing the Potential for Renewable Energy of National Forest System Lands. Oak Ridge: U.S. Department of Energy

Troen, I. and E.L. Petersen, 1989. European Wind Atlas. Roskilde: *Risø National Laboratory*

Sovacool, B. K. & Ratan, P. L., 2012. Conceptualizing the acceptance of wind and solar electricity.. *Renewable and Sustainable Energy Reviews,* Volume 16, p. 5268–5279.

Strachan, P. A., Lal, D. & von Malmborg, F., 2006. The evolving UK wind energy industry: critical policy and management aspects of the emerging research agenda. *European Environment*, Volume 16, pp. 1-18.

Skov & Landskab, 2010. Skove og plantager 2009*,* Hørsholm: *Skov & Landskab*.

Swedish Forest Agency, 2014. Swedish Statistical Yearbook of Forestry 2014*,* Jönköping: *Skogsstyrelsen - Swedish Forest Agency*.

Nordic Forestry, 2009. [Online]
Available at: http://www.nordicforestry.org/facts/Norway.asp
[Accessed 19 November 2014].

Forestry Comission, 2014. Forestry facts & Figures 2014*,* Edinburgh: *Forestry Comission*.

Sovacool, B. K. & Brossmann, B., 2010. Symbolic convergence and the hydrogen economy. *Energy Policy,* Volume 38, p. 1999–2012.

Arnqvist, J., 2013. Mean Wind and Turbulence Conditions over Forests*,* Uppsala: *Department of Earth Sciences Licentiate Thesis*.

Dellwik, E., Bingöl, F. & Mann, J., 2014. Flow distortion at a dense forest edge. *Quarterly Journal of the Royal Meteorological Society,* Volume 140, pp. 676 - 686.

Gardiner, B., 2004. Airflow Over Forests and Forest Gaps, *BWEA Tree Workshop Forestry*.

Junge, J. & Westerhellweg, A., 2004. Estimation of Zero Plane Displacement Heights in the Vicinity of a Forest, Wilhelmshaven, Germany: *DEWI GmbH*.

Brayshaw, D. J., Troccoli, A., Fordham, R. & Methven, J., 2011. The impact of large scale atmospheric circulation patterns on wind power generation and its potential predictability: A case study over the UK. *Renewable Energy,* Volume 36, pp. 2087 - 2096.

Boudreault, L.-É.et al., 2014. Canopy structure effects on the wind at a complex forested site. *Journal of Physics: Conference Series,* Volume 524.

Frank, C. & Ruck, B., 2008. Numerical study of the airflow over forest clearings. *Forestry Volume,* Volume 81, pp. 259-277.

Hui, S.-Y. & Crockford, A., 2008. Wind Profiles and Forests*,* Brussels: *EWEC*.

Raftery, P., LeBlanc, M. & Manning, J., 2004. WaSP Validation of Forestry Effects,. Glasgow, *BWEA Workshop on the Influence of Trees*.

Read, D. L. et al., 2013. The theory of planned behaviour as a model for predicting public opposition to wind farm developments. *Journal of Environmental Psychology,* Volume 36, pp. 70 - 76.

Devine-Wright, P., 2005. Beyond NIMBYism: towards an Integrated Framework for Understanding Public Perceptions of Wind Energy. *Wind Energy ,* Volume 8, pp. 125-139.

Enevoldsen, P., Sovacool, B.K., 2016. Examining the social acceptance of wind energy: Practical guidelines for onshore wind project development in France. *Renewable and Sustainable Energy Reviews*, Volume 53, p. 178-184

Saidur, R., Rahim, N., Islam, M. & Solangi, K., 2011. Environmental impact of wind energy. *Reneweable Sustainble Energy Review,* Volume 15, pp. 2423–2430.

Magoha, P., 2002. Footprint in the wind? Environmental impacts of wind power development. *Refocus ,* Volume 3, pp. 30-33.

Bright, J. et al., 2008. Map of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. *Biological Conservation,* Volume 141, pp. 2342 - 2356.

Chiras, D., Sagrillo, M. & Woofenden, I., 2009. Power from the Wind: Achieving Energy Independence. Gabriola Island: *New Society Publishers*.

Nadaii, A., 2007. ''Planning'', ''siting'' and the local acceptance of wind power: Some lessons from the French case.. *Energy Policy,* Volume 35, pp. 2715–2726.

Betakova, V., Vojar, J. & Sklenicka, P., 2015. Wind turbines location: How many and how far?. *Applied Energy* , Volume 151 , pp. 23–31

Jobert, A., Laborgne, P. & Mimler, S., 2007. Local acceptance of wind energy: Factors of success identified in French and German case studies.. *Energy Policy,* Volume 35, p. 2751–2760.

Nadaï, A. &. Labussière O., 2009. Wind power planning in France (Aveyron), from state regulation to local planning.. *Land Use Policy,* Volume 26. pp. 744-754.

Ladenburg, J. & Dubgaard, A., 2007. Willingness to pay for reduced visual disamenities from offshore wind farms in Denmark.. *Energy Policy,* Volume 35, pp. 4059–4071.

Ek, K., 2005. Public and private attitudes towards ''green'' electricity: the case of Swedish wind power. *Energy Policy ,* Volume 33 , pp. 1677–1689.

Ek, K., Persson, L., Johansson, M. & Waldo, Å., 2013. Location of Swedish wind power—Random or not?Aquantitative analysis of differences in installed wind power capacity across Swedish municipalities. *Energy Policy,* Volume 58, pp. 135–141.

Sperling, K., Hvelplund, F. & Mathiesen, B. V., 2010. Evaluation of wind power planning in Denmark - Towards an integrated perspective. *Energy ,* Volume 35 , pp. 5443-5454.

Khan, J., 2003. Wind power planning in three Swedish municipalities.. *Journal of Environmental Planning and Management,*Volume 46, p. 563–581.

IEA, 2013. Electricity Information, Paris: *International Energy Agency.*

Pettersson, F. & Söderholm, P., 2009. The diffusion of renewable electricity in the presence of climate policy and technology learning: the case of Sweden. *Renewable and Sustainable Energy Reviews,* Volume 13, pp. 2031-2040.

Ek, K. & Persson, L., 2014. Wind farms — Where and how to place them? A choice experiment approach to measure consumer preferences for characteristics of wind farm establishments in Sweden. *Ecological Economics ,* Volume 105 , pp. 193–203.

Pettersson, M., 2008. Renewable Energy Development and the Function of Law:A Comparative Study of Lega lRules Related to the Planning, Installation and Operation of Windmills , Luleå: *Luleå teknisk auniversitet.*

Pettersson, M., Ek, K., Söderholm, P. & Söderholm, K., 2010. Wind power planning and permitting: Comparative perspectives from the Nordic countries. *Renewable and Sustainable Energy Reviews,* Volume 14, pp. 3116 - 3123.

Pedersen, E. Persson, W. K., 2002. Störningar från vindkraft: Undersökning bland människor boende i närheten av vindkraftverk. , Gothenburg : *Department of Environmental Medicine, Gothenburg University.*

Söderholm, P., Ek, K. & Pettersson, M., 2007. Wind power development in Sweden: Global policies and local obstacles. *Renewable and Sustainable Energy Reviews,* Volume 11 , pp. 365–400.

Hellström, M., 1998. Vindkraft i Harmoni, Malmö: *Energimyndigheten.*

Warren, C., Lumsden, C., O'dowd, S. & Birnie, R., 2005. 'Green on Green': Public perceptions of wind power in Scotland and Ireland. *Journal of Environmental Planning and Environment,* Volume 46, pp. 853-875.

Warren, C. R. & McFadyen, M., 2010. Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. *Land Use Policy*, Volume 27, pp. 204 - 213

Phillips, J., 2015. A quantitative-based evaluation of the environmental impact and sustainability of a proposed onshore wind farm in the United Kingdom. *Renewable and Sustainable Energy Reviews,* Volume 49, p. 1261–1270.

Phylip-Jones, J. & Fischer, T., 2015. Strategic environmental assessment (SEA) for wind energy planning: Lessons from the United Kingdom and Germany. *Environmental Impact Assessment Review,* Volume 50, pp. 203-212.

Neuhoff, K., 2005. Large scale deployment of renewables for electricity generation. *Oxford Review of Economic Policy,* Volume 21, pp. 88-110.

Odeh, A. M. & Battaineh, H. T., 2002. Causes of construction delay: traditional contracts. *International Journal of Project Management,* Volume 20, pp. 67 - 73.

Wang, Y., 2006. Renewable electricity in Sweden: an analysis of policy and regulations. *Energy Policy ,* Volume 34 , pp. 1209–1220.

Cattin, R., 2012. Icing of Wind Turbines *,* Stockholm: *Elforsk*.

Jones, C. R. & Eiser, R. J., 2010. Understanding 'local' opposition to wind development in the UK: How big is a backyard?. *Energy Policy,* Volume 38, pp. 3106-3117.

Sovacool, B. K., Gilbert, A. & Nugent, D., 2014. Risk, innovation, electricity infrastructure and construction cost overruns: Testing six hypotheses. *Energy,* Volume 74 , pp. 906-917.

Sovacool, B.K., Enevoldsen, P., 2015. One style to build them all: Corporate culture and innovation in the offshore wind industry. *Energy Policy,*Volume 86, pp. 402–415

Sovacool, B. K., Nugent, D. & Gilbert, A., 2014 . Construction Cost Overruns and Electricity Infrastructure: An Unavoidable Risk?. *The Electricity Journal,* Volume 27, pp. 112–120

Dai, K. et al., 2015. Environmental issues associated with wind energy - A review. *Renewable Energy ,* Volume 75 , pp. 911-921.

Perks, M. et al., 2010. Wind Turbines & Trees: maximising net benefit in forestry settings. Aberdeen: *APF 2010 – Forestry Commission seminar series*.

Santos-Alamillos, F., Pozo-Vázquez, D., Ruiz-Arias, J. & Tovar-Pescador, J., 2015. Influence of land-use misrepresentation on the accuracy of WRF wind estimates: Evaluation of GLCC and CORINE land-use maps in southern Spain. *Atmospheric Research,* Volume 157, pp. 17 - 28.

Siyal, S. H. et al., 2015. Wind energy assessment considering geographic and environmental restrictions in Sweden: A GIS-based approach. *Energy,* Volume 83, pp. 447 - 461.

Möller, B., 2006. Changing wind-power landscapes: regional assessment of visual impact on land use and population in Northern Jutland, Denmark. *Applied Energy ,* Volume 83 , pp. 477–494.

Nadaï, A. & van der Horst, D., 2010. Wind Power Planning, landscapes and publics. *Land Use Policy,* Volume 27, pp. 181 - 184.

Girard, R., Laquaine, K. & Kariniotakis, G., 2013. Assessment of wind power predictability as a decision factor in the investment phase of wind farms. *Applied Energy ,* Volume 101 , pp. 609–617.

Lopes da Costa, J., Castro, F., Palma, J. & Stuart, P., 2006. Computer simulation of atmospheric flows over real forests for wind energy resource evaluation. *Journal of Wind Engineering & Industrial Aerodynamics,* Volume 94, pp. 603 - 620.

Casella, L., 2015. Performance analysis of the first method for long-term turbulence intensity estimation at potential wind energy sites. *Renewable Energy,* Volume 74, pp. 106 - 115.

Hameed, Z. et al., 2009. Condition monitoring and fault detection of wind turbines and related algorithms: A review. *Renewable and Sustainable Energy Reviews,* Volume 13, pp. 1 - 39.

Márquez, F. P. G., Tobias, A. M., Pérez, J. M. P. & Papaelias, M., 2012. Condition monitoring of wind turbines: Techniques and methods. *Renewable Energy ,* Volume 46 , pp. 169-178.

Tian, Z., Jin, T., Wu, B. & Ding, F., 2011. Condition based maintenance optimization for wind power generation systems under continuous monitoring. *Renewable Energy, Bind,* Volume 36, pp. 1502 - 1509.

Peste, F. et al., 2015. How to mitigate impacts of wind farms on bats? A review of potential conservation measures in the European context. *Environmental Impact Assessment Review,* Volume 51, pp. 10 - 22.

Loss, S., Will, T. & Marra, P., 2013. Estimates of bird collision mortality at wind facilities in the contiguous United States.. *Biol Conserv,* Volume 168, pp. 201-209.

Wang, S., Wang, S. & Smith, P., 2015. Ecological impacts of wind farms on birds: Questions, hypotheses, and research needs. *Renewable and Sustainable Energy Reviews,* Volume 44, pp. 599 - 607.

Sovacool, B. K., 2009. Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy,* Volume 37, p. 2241–2248.

Müller, J. et al., 2013. From ground to above canopy—Bat activity in mature forests is driven by vegetation density and height. *Forest Ecology and Management,* Volume 306, pp. 179 - 184.

Atlason, R. & Unnthorsson, R., 2014. Ideal EROI (energy return on investment) deepens the understanding of energy systems. *Energy ,* Volume 67 , pp. 241-245.

Caralis, G. et al., 2014. Profitability of wind energy investments in China using a Monte Carlo approach for the treatment of uncertainties. *Renewable and Sustainable Energy Reviews,* Volume 40, pp. 224 - 236.

Wiser, R. H., 1997. Renewable energy finance and project. *Energy Policy,* Volume 25, pp. 15-27.

Boqiang, R. & Chuanwen, J., 2009. A review on the economic dispatch and risk management considering wind power in the power market. *Renewable and Sustainable Energy Reviews ,* Volume 13 , pp. 2169–2174.

Gass, V., Strauss, F., Schmidt, J. & Schmid, E., 2011. Assessing the effect of wind power uncertainty on profitability. *Renewable and Sustainable Energy Reviews ,* Volume 15 , pp. 2677– 2683.

Boomsma, T. K., Meade, N. & Fleten, S.-E., 2012. Renewable energy investments under different support schemes: A real options approach. *European journal of operational research,* Volume 220. pp. 225 - 237.

Hasani-Marzooni, M. & Hamid Hosseini, S., 2011. Dynamic model for market-based capacity investment decision considering stochastic characteristic of wind power. *Renewable Energy ,* Volume 36 , pp. 2205-2219.

Morthorst, P., 1999. Capacity development and pro"tability of wind turbines. *Energy Policy,* Volume 27, pp. 779-787.

Barradale, M. J., 2010. Impact of public policy uncertainty on renewable energy investment: Wind power and the production tax credit. *Energy Policy,* Volume 38, pp. 7698–7709.

del Río, P., Calvo Silvosa, A. & Iglesias Gómez, G., 2011. Policies and design elements for the repowering of wind farms: A qualitative analysis of different options. *Energy Policy,* Volume 39, pp. 1897 - 1908.

Goyal, M., 2010. Repowering—Next big thing in India. *Renewable and Sustainable Energy Reviews ,* Volume 14 , p. 1400–1409.

Rader, N., 2007. Comments of the California Wind Energy Association on Wind Repowering, Berkeley.: *Berkeley University*.

Crawford, R., 2009. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. *Renewable and Sustainable Energy Reviews ,* Volume 13 , p. 2653–2660.

Tremeac, B. & Meunier, F., 2009. Life cycle analysis of 4.5MW and 250W wind turbines. *Renewable and Sustainable Energy Reviews ,* Volume 13, pp. 2104–2110

Martínez, E. et al., 2009. Life cycle assessment of a multi-megawatt wind turbine.. *renewable energy,* Volume 34, pp. 667 - 673.

Guezuragaa, B., Zaunera, R. & Pölzb, W., 2012. Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy,* Volume 37, p. 37–44.

Arvesen, A., Tveten, Å. G., Hertwich, E. G. & Strømman, A. H., 2009. Life-cycle assessments of wind energy systems. Stockholm, *EWEA Offshore*.

Schleisner, L., 2000. Life cycle assessment of a wind farm and related externalities. *Renewable Energy ,* Volume 20 , pp. 279-288.

Andersen, P., M., B. & Krogh, T., 2007. Managing Long-term Environmental Aspects of Wind Turbines: a Prospective Case Study. *Journal of Technology, Policy and Management,* Volume 7, pp. 339-354.

Albers, H., Greiner, S., Seifert, H. & Kühne, U., 2009. Recycling of Wind Turbine Rotor Blades - Fact or Fiction?, Wilhelmshaven: DEWI.

Lenzen, M. & Munksgaard, J., 2002. Energy and CO2 life-cycle analyses of wind turbines—review and applications. *Renewable Energy ,* Volume 26 , pp. 339–362.

Roques, F., Hiroux, C. & Saguan, M., 2010. Optimal wind power deployment in Europe—A portfolio approach. *Energy Policy*, Volume 38, pp. 3245–3256.

EWEA, 2015. Wind in power - 2014 European statistics, Brussels.: *European Wind Energy Association (EWEA).*

3 How can the risks associated with the siting of wind turbines be limited?

The first chapter defined the main differences in the patterns between wind farms located in forested areas versus other on – and offshore, and further introduced the challenges of deploying, operating and potential dismantling wind turbines in forested areas. This chapter seeks to introduce methods to limit the risks of siting wind projects in forested areas. Naturally, the output of this research has been defining the remaining studies conducted in the PhD, as a response to the lack of literature for those topics. The following papers have been used to answer Research Question 2:

3. *Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France. / Enevoldsen, Peter; Sovacool, Benjamin. / I: Renewable & Sustainable Energy Reviews, Vol. 53, 01.2016, s. 178-184.*

4. *From lidar scans to roughness maps for wind resource modeling in forested areas. / Enevoldsen, Peter.; Dellwik, Ebba; Arnqvist, Johan; Floors, Rogier; Davis, Neil. /To be submitted to Wind Energy Science. 2017*

3.1 Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France

The third journal article investigates methods for increasing the local social acceptance of onshore wind projects. It is based on input from semi-structured research interviews and insight from a French wind energy company. That company had noted that a lack of local social acceptance of wind projects increased the risk of failures, cost escalation, and project delays. In this study, we first summarize recent scholarship concerning local social opposition and acceptance of wind energy through a selected literature review and case studies of wind projects throughout Europe. We then use this data to create guidelines on how to increase the likelihood of social acceptance for onshore wind project development, and to inform current debates in the energy studies literature over the acceptance of wind energy and energy transitions. The third journal article has furthermore been used to create an understanding of social opposition, which has been applied in the remaining parts of the dissertation.

3.1.1   Introduction

During the past 40 years, wind power has grown into a major international industry (Ackermann & Söder, 2000; Christie & Bradley, 2012; Tabassum-Abbasi, et al., 2014) having 670,000 people employed worldwide in 2011 (Global Wind Energy Council, 2013) and roughly 225,000 wind turbines operating at the end of 2012 (Global Wind Energy Council, 2012). Furthermore in 2011, onshore wind power was the second-largest contributor to renewable electricity, after hydropower, producing 434 TWh (Global Wind Energy Council, 2012). Calculations reveal that wind energy had turbine installations worth about $37 billion in 2008 (Bilgili, et al., 2010). The developments in the wind industry are furthermore expected to rise dramatically over the next decades (Christie & Bradley, 2012) due to a global push to decarbonize energy systems (Sovacool, 2014a). The social acceptance of renewable electricity, however, remains under-explored and perhaps underappreciated in the energy studies literature (Sovacool, 2014a); Sovacool, 2014b; Aitken, 2010).

France reflects both the promise of wind power and this conundrum of social acceptance. France have a history of harnessing wind energy, as in 1800, about 20,000 wind mills were operating. For the past decade the country has experienced a substantial growth in the wind industry (IEA, 2012; Wilkes & Moccia, 2013). There are currently 723 wind farms located in France (IEA, 2012), most of them in the northern and western region, most likely due to the higher wind speeds and flat terrain in these areas. The entire installed wind power capacity in the end of 2012 in France amounted to 7.6 GW (IEA, 2012). This places France in the global top ten of countries with most installed wind power (IEA, 2012; Wilkes & Moccia, 2013).

However, during 2012 installers added only 757 MW of capacity to this base (IEA, 2012), far less than in most other European countries (Wilkes & Moccia, 2013).The disappointing numbers appeared despite the fact that French energy policy favors wind power more than ever (Nadaï & Labussière, 2009; Huberta & Vidalenc, 2012). The lack of installed wind power capacity in France has led to several studies (Szarka, 2007; Jones, 2006) focusing on the difficulties of developing wind farms in France, such as; the complex terrain in the southern and eastern part of the country, the political favoring of nuclear energy (Szarka, 2007; Jones, 2006) and environmental considerations regarding and impact on humans and animals (Nadaï & Labussière, 2009). However, another obstacle seems to be more important when investigating the lack of developed wind farms in France: a lack of social acceptance (Nadaii, 2007; Roques, et al., 2010; IEA, 2010; Jobert, et al., 2007; Nadaï & van der Horst, 2010). Each wind project in France, for instance, depends on the acceptance from the local mayor and city council, who acts in the interest of the local inhabitants (Nadaï & Labussière, 2009). In sum, local inhabitants need to be in favor of wind projects in order for them to proceed.

Therefore, in this study we ask: how can onshore wind projects achieve greater social acceptance in France? The article begins by summarizing recent scholarship concerning social acceptance of wind energy before presenting a synthetic guideline on how to realize this social acceptance in practice.

3.1.2   Methods

To collect data for our study, we relied on two interconnected methods: semi-structured research interviews in France, and a targeted literature review. We conducted 19 in-depth interviews with "elite" stakeholders (those with significant power and legitimacy) in France over the period September 2013 to January 2014. Stakeholders were carefully chosen, based on the experience of the wind project developer and the results discovered by Nadaii & van der Horst (2010) and Jobert, et al.

(2007). Figure 19 offers more details about our respondents, which we kept anonymous to protect confidentiality, something mutually agreed upon at the start of each interview.

Figure 19 Number of stakeholders interviewed
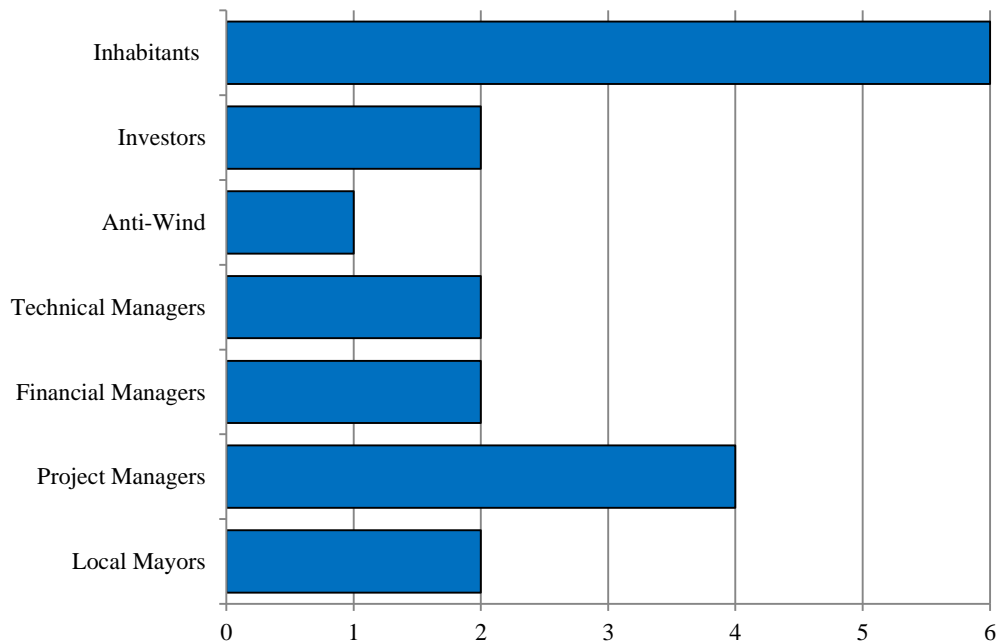
The majority of the interviews were conducted via face-to-face meetings. The interviews with the president of the European Platform Against Wind (EPAW) and a few follow-up interviews with project managers from the wind project developer were conducted through phone, following the guidelines and principles from Körmendi, et al. (1986) to ensure data quality. Our most significant interviews were the ones performed with project managers and financial and technical responsible employees from the wind project developer. The employees of the wind project developer were asked about the general development principles of French onshore wind projects. The questions were based on theories for generic wind project development (Nielsen, 2002; Wizelius, 2007; Manwell, et al., 2009), including the costs, risks and the importance of social acceptance. The other stakeholders were asked questions that revealed their acceptance (or lack of acceptance) of onshore wind projects. Furthermore, possible activities increasing social acceptance were discovered.

To triangulate our data, the interviews were supplemented with a search of the peer-reviewed literature on the topic of social acceptance and wind energy. Using the Scopus database, we searched for the word "wind energy" together with one of the following set of words or combinations in the abstracts or keywords of articles: acceptance, social acceptance, adoption, attitudes, approval, opposition, and NIMBY. Scopus was chosen since it is a database of peer-reviewed literature that includes much of the social science in addition to the natural science literature. To supplement our findings from Scopus, we identified complementing examples found in publicly available reports and our research network. The result is a literature review theorizing social acceptance by dividing it into reasons for opposition and contributing factors for acceptance.

The theorizing of social acceptance in this research can be used for investigating the social acceptance in any country, however, when defining specific reasons for opposition, and possible methods for

increasing social acceptance, a research approach like the one applied with interviews with "elite" stakeholders offers an established tool for soliciting perceptions and identifying obstacles.

3.1.3   Examining the Key Concepts of Social Acceptance

One poll found that a large percentage of the French people supported wind energy (Roques, et al., 2010).Yet publics have in many instances protested, and even postponed and "killed", the development of wind farms in France (Nadaï & van der Horst, 2010), where the overall concern is the wind turbine's impact on the landscape. Why does this occur? To provide an answer, this section of the study summarizes the outcome from semi-structured research interviews conducted with stakeholders from the French wind industry. In addition, a comprehensive literature study has revealed recent advances in scholarship looking at the social acceptance (or lack of acceptance) to onshore wind projects, justifies France as our case study, and then synthesizes lessons from three case studies involving Scotland and France.

3.1.3.1   *Theorizing Social Acceptance*

Before recommending actions on how to achieve social acceptance one needs to clarify the extent and importance of social acceptance for the development of onshore wind projects. The reason why they oppose to wind turbines (Roques, et al., 2010; Nadaï & van der Horst, 2010), may be caused by a process known as "Not In My Backyard," or NIMBY (Hellström, 1998), further elaborated on in Table 16 below.

Table 16 Four types of social opposition to wind energy (Hellström, 1998)

The Four Types of NIMBY	
NIMBY 1	Positive attitude to wind power installations in general, but negative attitude to installations in the immediate vicinity.
NIMBY 2	Generally negative attitude towards wind power
NIMBY 3	Positive attitude to plans to develop wind power, which change to negative when there are plans to install wind turbines in the vicinity.
NIMBY 4	Negative attitude to the planning procedure rather than to wind power

As readers of this journal may know, acceptance and rejection at the scale of local communities tends to revolve around issues related to local environmental quality, procedural justice, distributional justice, and trust (Sovacool, et al., 2014; Greenberg, 2014), yet at larger scales involve broader socio-political and market dimensions related to public approval, electricity prices, profitability for investors, and the ability to improve energy security (Sovacool & Ratan, 2012; Wustenhagen, et al., 2007).

Some forms of opposition or NIMBY-ism can cut across community, socio-political, and market dimensions simultaneously. Landowners may oppose a wind farm because they fear it will lower their property values and increase their electricity bills; environmentalists because they believe it could harm birds and require fossil-fueled power stations to "backup" intermittent wind generation; investors because they worry about delays in project implementation; politicians and regulators about job losses and public controversy. These forms of opposition fuse community, environmental, economic, and political concerns together (Sovacool, 2009).

Two prevailing factors that seem to influence the phenomenon of NIMBY, or the lack of it, are location and time.   Breukers and Wolsink (2007) found differing attitudes towards wind energy in the

Netherlands (where public opposition was more about the prospect of volatile electricity prices and an exclusionary method of approving wind projects), the United Kingdom (where opponents were critical of the "neo-liberal" approach to wind development), and Germany (where the public was primarily concerned about protecting the environment). Furthermore, extensive surveys of public opinion related to renewable energy (and other power plants) have also revealed that attitudes and values change over time. One longitudinal study looked at U.S. public opinion relating to energy sources and priorities from 1974 to 2006 and noted that public attitudes as a whole have shifted (Bolsen & Cook, 2008) on the whole to be more positive towards renewable source such as wind and negative towards fossil fuels and nuclear. This scenario is not yet present in France, although changes are expected to happen (Szarka, 2007; Jones, 2006). Moreover, research suggests that opposition to wind projects changes significantly before and after projects are completed, with projects contentious at the planning stage but generally accepted after they have been constructed. Put another way, local people become more favorable towards wind farms after their construction and the degree of acceptance tends to increase in proximity to the wind farm. Devine-Wright (2005) performed a study on the local acceptance in a wind project before, during and after construction of the wind turbine, and found that the acceptance generally decreases close to the commencement of the project, but then rebounds over time, as Figure 20 depicts. The same result has been found in a case study from Nadaï & Labussière (2009) who discovered that local inhabitants found the need for complaining about the wind turbine project just before the public enquiry round.

Figure 20 Sequential phases of local acceptance in a wind project (Devine-Wright, 2005)
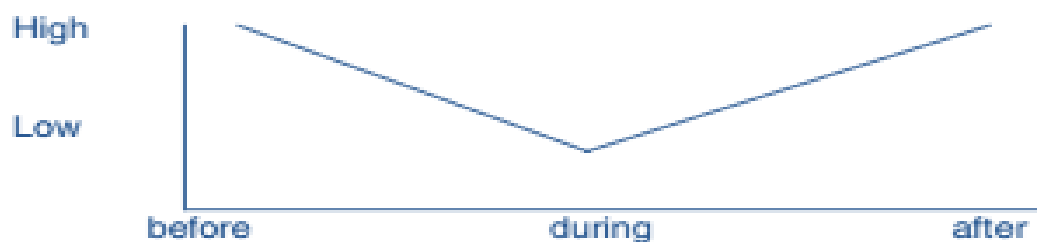
Yet NIMBY opposition and social acceptance is a complex topic about more than space and time. For instance, various studies of public attitudes towards wind energy from Europe and North America have found that:

- People with no specific experience with wind energy are more likely to oppose it, overestimate its costs, and underestimate its benefits;
- Middle aged people and risk-averse people are more likely to oppose projects than young or old respondents;
- Opponents tend to place a higher value on aesthetics than on other aspects such as climate change or employment effects;
- Acceptance is stronger when turbines are believed to work ("spinning" turbines are more favored than "idle" ones);
- The more expensive a group of people perceive a particular project the more they are likely to oppose it in their community;
- City dwellers are more likely to oppose projects than country dwellers (one explanation is that urban residents have a more romantic view of the countrywide whereas rural residents view it as a resource to be harnessed);

- The same person or group can simultaneously support the *idea* of wind power (holding a positive view) but oppose the construction of a *particular* wind farm (holding a negative view), creating a "gap" between public support and private behavior;
- Opposition to projects generally declines when respondents are given a rationale for building a new wind farm as opposed to asking them questions in the abstract;
- Providing incentives for local citizens to invest in or own part of a project, or inviting them to participate in planning and siting procedures, can strongly influence social acceptance;
- Residents of "stigmatized" or degraded landscapes are more likely to welcome facilities that they see as green or supportive of the local economy (Bell, et al., 2005; Walker, 1995; Krohn & Damborg, 1999; Hirsh & Sovacool, 2013; Warren, et al., 2005).

A study in Great Britain (Warren, et al., 2005) has showed that public attitudes towards wind turbines and landscape often cause a "green or green" dilemma. This phenomenon is experienced when locals living nearby a proposed wind farm have to choose between a "global good", in the reduction of CO_2, and the "local bad", with the wind turbine's impact on the local landscape (Warren, et al., 2005). This is especially the case with wind turbines as they are very visible in the landscape (Nadaï & van der Horst, 2010), due to their size which furthermore is increasing (Manwell, et al., 2009). In essence, these studies challenge the notion that the NIMBY phenomenon occurs uniformly.

Other research has proposed that the concept NIMBY is incomplete and insufficient to truly explain social acceptance. One study surveyed public attitudes toward wind energy in Ireland and Scotland and found an "inverse NIMBY syndrome" where those with wind farms in their backyard vigorously praised and supported them (Warren, et al., 2005). Ansolabehere and Konisky (2009) documented that NIMBY reactions are highly variable and depend on demographic characteristics of the public, their perceptions of cost and environmental harm, individual attitudes concerning risk, and the types of facilities or technologies involved. Wolsink (2000 & 2007) found that a true "NIMBY attitude," defined as a tendency for people to frame their objection to wind turbines in terms of individual utility or selfishness, accounted for only one-quarter of the stated reasons for opposition. Instead, other studies have found that wind turbines were primarily accepted or rejected based on broader factors relating to public interest and the interests of others as well as notions of fairness and equity (Walker, 1995; Krohn & Damborg, 1999).

Table 17 draws from and synthesizes this literature, and it proposes that the social opposition to onshore wind turbines will cut across environmental, aesthetic, and socioeconomic dimensions. We hold that the inverse holds true: wind turbines with minimal environmental impact or environmental benefits, which are aesthetically pleasing, and contribute to local economies will by and large be socially accepted.

Table 17 Synthetic reasons for social opposition to wind energy

Dimension	Component(s)	References
Environmental impact	Flora and Fauna	(Saidur, et al., 2011)
	Reduction of wildlife	(Magoha, 2002; Bright, et al., 2008; Chiras, et al., 2009)
	Felling of trees	(Devine-Wright, 2005)
Visual Impact	Size, Color and Shape of the wind turbine	(Roques, et al., 2010; IEA, 2010)
	Number of wind turbines	(Wizelius, 2007)

	Noise and Flicker effects	(Manwell, et al., 2009)
	Usage of Landscape	(Jobert, et al., 2007)
	Involvement in placement	(Nadaï & Labussière, 2009)
Socioeconomic Impact	Tourism	(Jobert, et al., 2007; Ladenburg & Dubgaard, 2007)
	Property and land values	(Jobert, et al., 2007)
	Local benefits	(Nadaï & Labussière, 2009)
	Lack of information from developer	(Nadaï & Labussière, 2009)
	Political – and Market acceptance	(Roques, et al., 2010; Sovacool & Ratan, 2012)
	Number of wind projects in the area	(Jobert, et al., 2007)

3.1.3.2   Activities for achieving local acceptance of wind turbines

This subsection of the paper analyzes three different case studies conducted in Scotland and France, in order to find answers on how local acceptance can be achieved in French wind projects. Warren & McFadyen (2010) investigated how public ownership affect public attitudes to wind energy. They found subtle but meaningful differences between public-owned and private developed wind projects, which took place in two different areas; Gigha and Kintyre, Scotland. Scotland is facing the same problems as France (Nadaï & Labussière, 2009; IEA, 2010; Jobert, et al., 2007), regarding the public complaints about wind turbines polluting the landscape (Warren & McFadyen, 2010). At the same time Scotland is one of the best onshore wind locations in Europe (Wizelius, 2007; Petersen, et al., 1989), due to the constant high wind speeds (Manwell, et al., 2009). The Scottish case study revealed that social acceptance of wind turbines is higher in areas where locals are directly committed as stakeholders with ownership (in Gigha), than in areas where locals are not committed by the wind project developer (Kintyre). Acceptance, in other words, is based on the fact that the inhabitants felt ownership towards the wind project (Warren & McFadyen, 2010).

In continuation to this, another suggestion very relevant to this research came from Nadaï & Labussière (2009), who proposed that local non-stakeholders, meaning locals without impact and ownership in the project, should be invited to participate in the planning process. This was suggested, in order to make proposals for the location of the wind turbines in landscape, which in the case of a wind project in Aveyron, France, ended with a public enquiry without the usual arguments against wind turbines, due to the impact on the local landscape (Nadaï & Labussière, 2009). This research furthermore suggests that the usage of local contractors may have an impact on the local acceptance of the wind project.

The third case study (Jobert, et al., 2007) was performed on three different French sites and suggested, that eight important factors for local acceptance must be questioned and analyzed, as these facors often causes lack of social acceptance (Jobert, et al., 2007). The factors are divided into two groups; *Site* and *Project Management* (Jobert, et al., 2007) and are presented in Table 18.

Table 18 Factors contributing to the social acceptance of wind energy, inspired by Jobert, et al. (2007)

Site		Project Management	
Factors	Topics to analyze	Factors	Topics to analyze

Visual impact on the landscape	Studies (Wizelius, 2007; Manwell, et al., 2009; Petersen, et al., 1989) have investigated that Wind Turbines (with a hub height of 80-100m) are the visual dominating factor in the landscape, at a distance up to 2-3 km and that the wind turbines melts into the landscape at a distance of 12 km.	Ownership of the wind project	If possible, the local inhabitants should have the opportunity to invest in the wind project.
Preuse of place	The area might have a sentimental value to the local inhabitants, which can create negative attitudes towards a wind project	Information level	The local inhabitants needs to be informed of the process in the development of the wind project.
Ownership of the location	Is it owned by locals, by the commune, or is it owned by an outside private investor. This is important as projects owned, or partly owned, by locals and the commune will gain more acceptances.	Local network in favor of wind energy	The study found that a strong local network supporting the development of wind projects could increase the public acceptance
Local economy	What are the economy based on; Tourism and Farming etc., and what are the economic situation in the area. This is important as wind turbines is expected to have a positive impact on the local economy. However may locals fear, that the wind turbines will destroy their local business of farming and tourism. Danish case studies (Ladenburg & Dubgaard, 2007) have stated that wind turbines have almost no negative effect on local tourism.	Integration of the wind project developers	The wind project developer needs to be visual in the area, by for instance involving local contractors.

3.1.3.3   *Wind Energy in a French Context*

Based on the semi-structured research interviews, it has been possible to specify social acceptance in a French context. In order to recommend actions for increasing the likelihood of local acceptance in France, one needs to also understand the stages of a French wind project, in order to find where in the process social acceptance matters the most. The timeline presented in Figure 21 has been constructed using the knowledge of three project managers in a French wind project development company from a stage gate point-of-view. The findings has been further verified by theoretical descriptions of French wind projects.

Figure 21 Timeline of a French onshore wind project
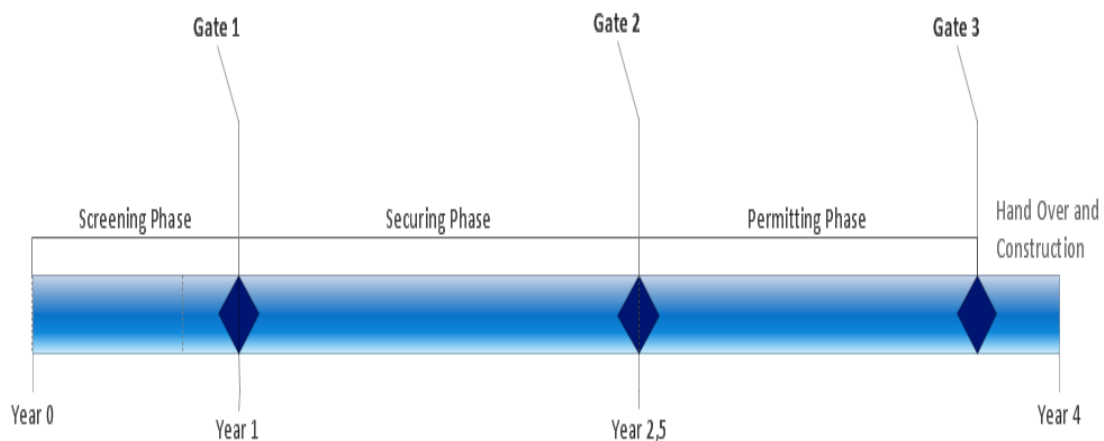
The project managers in the wind project development company agreed that the average French wind project takes four years to develop, from the point where the company starts to investigate an area, and until the project is sold or at least is ready for construction. The project managers furthermore calculated an average development time of each of the three overall stages (*Screening*, *Securing* and *Permitting*) for this period. Each stage has its own sets of important actions and targets which need to be fulfilled in order to develop a wind project with success. The targets associated to local acceptance are listed below in a hierarchal order after where they are performed in the process.

Gate 1: The local mayor's approval of the wind project

Gate 2: The acquiring of land needed for the wind project

Gate 3: The completion of the public enquiry round

Each target is affected by the local acceptance, but one remains extremely important, as the public inquiry round is held after the expensive wind measurement campaign, and the environmental studies needed for building permits. The other targets referring to technological and businesses matters have not been included in this research, although the cost and resources spent for these activities are the reason why risk-lowering activities for social acceptance need to be considered. Figure 22 depicts the development cost for an onshore French wind project, and it emphasizes the importance of having a successful public enquiry round without having to redo the costly studies in the Permitting stage.

Figure 22 Cost development of a French onshore wind project
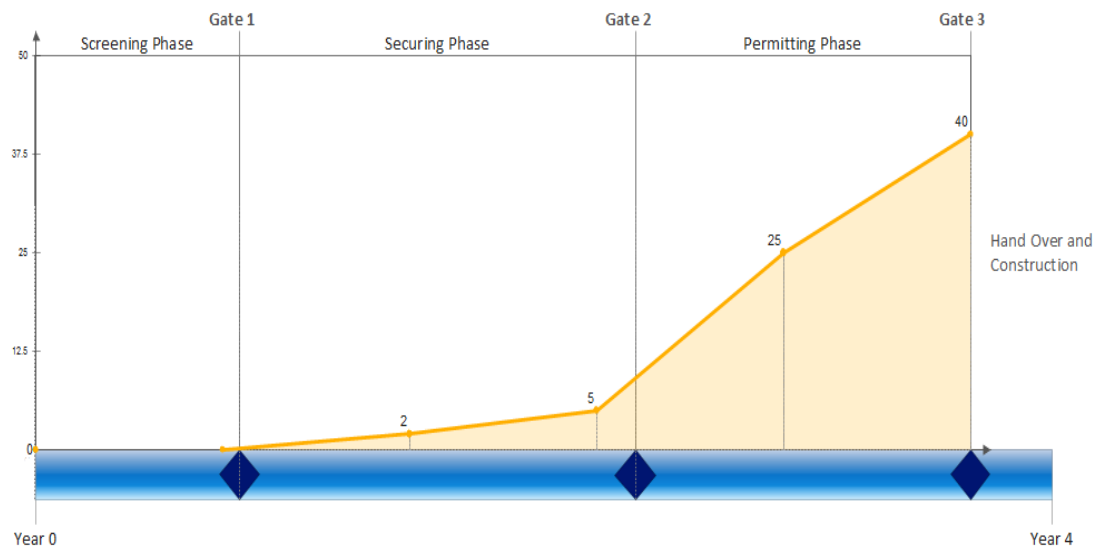
3.1.4   Conclusions and policy implications

Lack of social acceptance remains a major constraint facing onshore wind project development in France, despite recent political efforts (Jones, 2006; Nadaii, 2007; Roques, et al., 2010). We have found that social opposition against windfarms exists in France, as both local policy decision makers and inhabitants are likely to oppose wind projects. However, the social acceptance of wind power can be achieved by a range of activities, generally by informing and involving a broad consortia of stakeholders. We have confirmed this hypothesis through the empirical data presented in this study, and also presented a guideline with actions for how developers ought to consider proceeding with the development of wind farms in France and beyond. With this in mind, we offer two conclusions.

First, having both defined the reasons for opposition and acceptance of wind project, it is possible to construct a guide for achieving local acceptance of onshore wind projects. As our study has demonstrated, wind projects need public support, especially willingness of local inhabitants and the mayor (Khan, 2003). In addition, community ownership can be associated with a local social acceptance, and the inclusion of local stakeholders can positively influence community acceptance. Figure 23 illustrates when in the development project such activities are needed, and which requirements the activities should fulfill, in order to make wind projects more attractive for the public sector. Each action presented in Figure 23 is described in Table 19 in order to serve as a template that both researchers and project developers can utilize to better comprehend the process of social acceptance.

Figure 23 Activities needed for public acceptance of wind farms in France
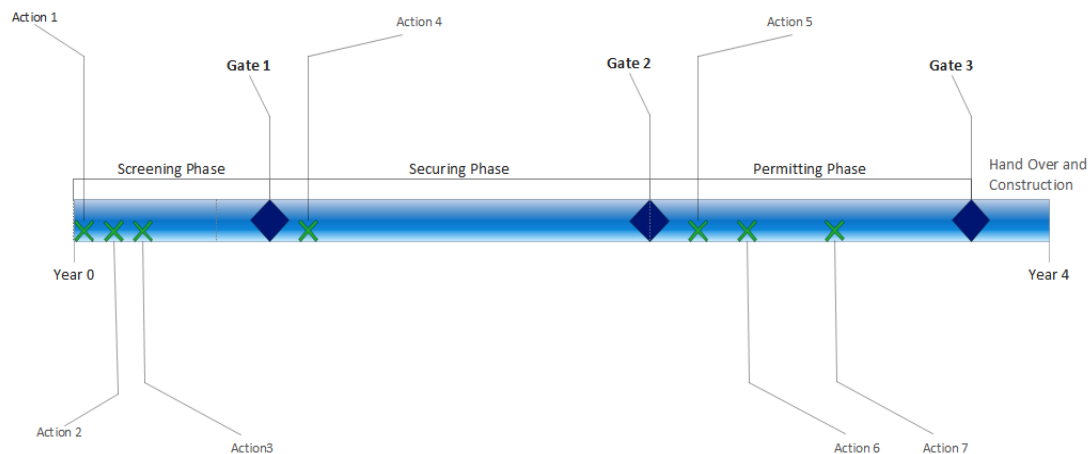
Table 19 Recommendations for accelerating the social acceptance of wind farms in France

Phase	Sequential Action(s)	Impact	Stakeholder(s) supporting the impact	Literature supporting the impact
Screening	Invite the local mayor(s) to an information meeting regarding the development of a new wind project	Engenders local political support	Mayors, Project Managers	(Khan, 2003)
	All inhabitants should be invited to a similar information meeting regarding the location of the project and possible involvement	Enhances broader social acceptance	Inhabitants, Project Manager	(IEA, 2010; Jobert, et al., 2007; Warren, et al., 2005)
	Once stakeholder screening processes are completed, solicit the mayor for project approval	Facilitates licensing and permitting	Project Manager, Investor	
Securing	Invite local contractors to construct the wind farm and engage industry	Commits local stakeholders through economic benefits	Inhabitants, Mayor	(Nadaï & Labussière, 2009 Jobert, et al., 2007; Devine-Wright, 2005; Warren & McFadyen, 2010)
Permitting	Have a final information meeting, where inhabitants can share their worries	Enables the incorporation of feedback and avoidance of future	Investor	(Nadaï & Labussière, 2009; Devine-Wright, 2005)

	about the project	complaints and public enquiries		
	Connect the project to local investment opportunities	Ownership removes the risk of public enquiries	Investor, Project Manager, President of EPAW	(Nadaï & Labussière, 2009; Warren & McFadyen, 2010)

The activities in Table 19 have been specified for the French wind market using the semi-structured stakeholder interviews. However, it is believed that the results of this research can be applied to other countries, such as some of the growing wind nations, like Norway and Sweden (Global Wind Energy Council, 2012), where managing public perception is becoming a more intractable challenge for the wind industry (Khan, 2003; Neuhoff, 2005; Pettersson & Söderholm, 2009). Furthermore, the methodology of interviewing key stakeholders and combine their wishes with peer-reviewed literature on social acceptance are believed to be a future methodology that other researchers can employ to better triangulate their data.

Second, and building from the first conclusion, is that our results suggest that whether local attitudes towards wind power translate into social acceptance or opposition is never predetermined, and can be successfully managed, even modelled, when given sufficient attention during the planning and implementation process. Acceptance need not be anathema to wind project investors and developers across Europe. What some see as an obstacle can be re-contextualized as an opportunity.

3.2 From lidar scans to roughness maps for wind resource modeling in forested areas.

The fourth paper introduces the demonstration of a method to convert high resolution tree height maps to roughness maps suitable for WAsP. The introduced conversion method was examined and compared to four online available roughness maps based on land use classes. The comparison was carried out using seven meteorological masts. The meteorological masts have been measuring wind conditions in various heights in a forested area located in the central part of Sweden. The test site has a large concentration of coniferous trees positioned in a heterogeneous forest formation, which is considered ideal to test the accurateness of the data sources. Testing the different data sources is important, as the consequences of applying misleading roughness lengths can impact the expected performance of wind turbines. The results of the research revealed that the tree height-based maps resulted in a closer agreement with observational data compared to standard conversions from land use classes. This finding furthermore stresses the importance for siting engineers to collect appropriate site data that describes the forest. Besides comparing approaches for construction of roughness maps, the study also examined the importance of spatial resolution, from where it was discovered that no clear improvement was found when increasing the roughness map resolution for z0. However, it was discovered that in order to apply a displacement height, a high resolution tree height map is required. The introduced displacement height provides even better results when applied with a high resolution roughness map. The fourth journal article is thereby seeking to understand and limit the risk of resource assessments over forest canopies.

3.2.1 Introduction

Ever since the first multi-megawatt wind turbine was installed in 1978, the continuous increase of wind turbines' hub heights has rendered it possible to deploy wind turbines in locations that were previously considered nonviable for wind projects such as forested sites (Enevoldsen, 2016). Studies have even suggested that wind project development in forested areas face fewer of the generic risks than other onshore wind farms, due to those projects higher cost for land acquirement and socio-political opposition (Enevoldsen, 2016). These risks are raising concerns for the wind industry in countries with a high share of installed wind farms (Enevoldsen & Valentine, 2016). While these risks are reduced, there is recognition that estimating the wind conditions over forested sites remains a challenge for wind project development in forested areas. This study focuses on reducing the challenge by introducing highly accurate surface information into a standard siting tool.

Although much progress has been made in terms of estimating the wind conditions over forested areas using RANS and LES models (Sogachev & Panferov, 2006; Patton & Finnigan, 2012), many siting engineers still rely on the faster modeling tools such as the WAsP model (Petersen, et al., 1989). In the WAsP model, the forest effects on the wind flow are parametrized using an aerodynamic roughness length, z0, and displacement height, d. How to correctly choose these parameter values for WAsP was the topic of Dellwik, et al. (2006), who found that previous recommendation of roughness values were too low for forested sites. In this study, the WAsP predictions were validated against cup and sonic anemometer mast data taken mainly over small and dense beech forests, but the masts were only around 50m tall which is far below the typical hub height for wind turbines in forests. Dellwik, et al. (2006) based their z0 and d estimates on a method suggested by (Raupach, 1994 & 1995), which rely on accurate knowledge of forest height, typical tree distance and crown diameter, Hui & Crockford (2008), successfully tested several other methods based on a tree height information only.

For the tall modern wind turbines, large areas influence the flow over the rotor. To apply a tree-height dependent roughness estimate, it is therefore necessary to find accurate tree height information extending kilometers from a potential site. Whereas such information has typically not been readily available, the rise of airborne lidar technique for surface characterization has enabled the acquisition of forest structure data with a new level of accuracy. Typical outputs from an airborne lidar survey are digital terrain models (DTM) and digital surface models (DSM), indicating the height of vegetation and buildings on the surface. Early surveys of the commercial DSM models in a forested area showed an underestimation of the tree top height, whereas the raw data from the scans showed to be more precise compared to in-situ measurements. An approach for processing the raw data, the "point cloud", for wind modeling was presented by Boudreault, et al. (2015). Boudreault, et al. (2015) processed the raw data to fit a distributed drag force parameterization of the forest which is commonly used in Computational Fluid Dynamics models. In this study, our aim is to derive z0 and d from tree height maps based on the point cloud data.

In Dellwik, et al. (2006), the effect of the displacement height was added into the modeling framework by reducing the height of the observations by d. This approach can be defended as long as the potential wind turbine site is located far away from a forest edge. Typically, masts with wind observations for wind energy applications are located in clearings, and the forest edge is close to the observations. In this case, the dynamic effect of the forest edge will affect the flow. Moreover, the increasing swept area of the wind turbine, now ranging with more than 100 meters between lower and upper tip height, forces the wind industry to estimate changes in wind conditions in the vertical boundary layer, especially since the atmospheric boundary layer is expected to be deeper in neutral conditions over forested areas (Arnqvist, et al., 2015). In the current study, we take the displacement height into account by adding it to the DTM. This has the further advantage in that it enables a quantification of the speed-up over forest edges (Dellwik, et al., 2014).

This research is therefore considered important, as there is a recognition that estimating the wind conditions over forested sites remains a challenge for wind project development in forested areas (Bergström, et al., 2013), despite decades of research that has provided knowledge about the wind flows above tall forest canopies (Hicks, et al., 1975, Jarvis, et al., 1976, Raupach and Thom, 1981, Baldocchi, 1988, Mölder, et al., 1999, Arnqvist 2015). However, as summarized by Enevoldsen (2016), the scientific approaches for determining the roughness length and displacement height for trees varies. Furthermore, most of these studies, especially those dated more than two decades ago, focused on surface-layer theory and turbulence near the canopy, which despite its relevance were not targeting wind resource assessment software, such as WAsP. Perhaps as a response to the academic disagreement, the wind industry has adopted satellite data, which provides freely available land use models. This data input is applied despite providing coarse spatial resolutions, and conversions of land use classes to roughness length values, which are significantly lower than what has been presented by previous research studies, despite the recommendations more than a decade ago of increasing roughness lengths for trees (Dellwik, et al., 2006).

Failing to estimate the impact of the trees on the wind conditions above the forest canopies, may cause the wind turbine to perform different than predicted (Enevoldsen, 2016).

As a response to the lack of consensus in academia and industry, this research aims at revealing the importance of surface features for forest modeling using roughness lengths and displacement heights. The study is carried out by examining and comparing existing land use model against a conversion method based on high detail surface data converted into roughness lengths.

3.2.2 Wind measurements

The following section introduces the measurement and filtering of the meteorological masts applied in this research.

3.2.2.1 *Site and instrumentation*

The site investigated in this study is located on two forested ridges in central Sweden (Figure 24), approximately 140~km from the Baltic sea coast. The site has two 60m and five 100m high meteorological masts that were instrumented at several height with cup anemometers and wind vanes (Table 20). The observational campaign started at either December 2008 or November 2011, and all meteorological masts were simultaneously operational between February 23rd 2009 and February 18th 2010. It is this approximately a one year period that is the focus of the current study. Three types of cup anemometers were used on the masts. All masts used NRG #40 anemometers, manufactured by NRG Systems, Inc., for the lower measurements on the masts. The 60m masts each had two WindSensor (Risø) P2546A anemometers top mounted, while the top mounted anemometers on the 100m masts were Thies First Class anemometers.

Table 20 Instrumentation overview at the site.

Met. Mast No	Top	Profile	Heights (m)
1	Risø P2546A	NRG40	59.0, 59.0, 57.0, 44.5, 31.5
2	Risø P2546A	NRG40	59.0, 59.0, 57.3, 44.0, 32.1
3	Thies First Class	NRG40	100.7, 100.7, 96.4, 80.7, 57.8
4	Thies First Class	NRG40	100.8, 100.8,96.4, 80.8, 57.7
5	Thies First Class	NRG40	100.8, 100.8,96.4, 80.9, 57.8
6	Thies First Class	NRG40	100.8, 100.8,96.4, 80.7, 57.6
7	Thies First Class	NRG40	100.8, 100.8,96.4, 80.9, 57.8

3.2.2.2 *Treatment of observational wind data*

An initial data screening showed significant inconsistencies in both the cup and vane data. The erroneous data were prevalent during winter time, and we assume that the most likely cause of error is ice growth on the anemometers. During these periods, the cup anemometers would typically freeze at a constant value, but sometimes, due to partly thawing, the cup would continue to turn at a much lower rate than before giving anomalous wind speed values. In order to remove these episodes, the following data screening steps were applied:

1. Removal of periods when the cup anemometer was clearly malfunctioning. This step was based on visual inspection of the whole series, the installation reports from each mast and the requirements that $0 \leq U \leq 50 \ m \ s^{-1}$ and $I_u < 1$, where U is the wind speed and I_u is turbulence intensity.

2. Removal of periods where instruments were giving constant output by requiring that $U_i \neq U_{i \pm 1}$. where i denotes a 10 minute block average.

3. Removal by ice-affected data by comparing pairs of cup anemometers in each mast. A mean gradient between all pairs of anemometers was calculated for data between May and September, which was considered to be ice free. Only data points within $\pm 3\sigma$ of the mean gradient, where σ is the standard deviation, for at least three other anemometers at the same tower were retained.

Data passing these criteria were associated with a quality control value QC = 1. The above steps removed a great part of the data in the winter period. After applying this quality control filter, the NRG cup anemometer data was still systematically lower than expected when compared to the top anemometers. We attribute this difference to both tower shadowing and a systematic small instrumental error. To correct for this effect, the NRG cup data was extrapolated to match the level of the top anemometers, using the following method:

1. Determine which top cup anemometer data to use based on wind direction.
2. Calculate the expected top wind speed from the profile cups by linear extrapolation from the two highest profile cups.
3. Define a correction factor as the ratio between the actual top cup measured wind speed and the profile estimated value for each 10-minute period.
4. Apply the correction factor to all wind speeds in the profile.

The final data cleaning step required that all cup anemometers had simultaneous values of QC = 1, to enable cross predictions in the model. After applying all of these filtering steps, 8764 10-minute mean wind speeds were available at each height and mast. The WAsP model requires an 'observed wind climate' file format, i.e. the frequency of the wind for each wind speed and direction bin. To generate these, we used a data discretization of 1 m s-1 for wind speed and 30º for the wind direction.

3.2.3   Site land cover description

The following section introduces the site applied in this research, as the collection and analysis of the terrain data is presented.

3.2.3.1   *Estimating elevation and forest height*

The area is characterized by industrial forests, intersected by lakes and rivers. This leads to a patchy forest cover (Figure 24, top left) that is difficult to characterize using existing open-source global coverage databases, or even by site visits. However, the surface characteristics can be described accurately by airborne laser scans. Differences from the approach by (Boudreault, et al., 2015) include: a new filtering algorithm to discard data outliers, removal of the overlap between the areas that the points are sorted into, and a change to the digital terrain model algorithm. The area at and around the site was scanned by airborne laser, thereby closely overlapping with the main observational period. The data were first processed on the DTU computer cluster to output a digital elevation model (DTM), a digital surface model (DSM) (for forest height) and a map of all the water areas (lakes and rivers) at 20x20 meters resolution, using the method described above. The median elevation z_m of all ground points inside the 20x20 meters area was selected for the DTM. The DSM forest height h grid was estimated as $h = \max(z_m - z_i)$, where h is the forest height and z_i indicates the vertical coordinate of all points i inside the area.

Figure 24 Orography (left) and tree height map (right) of the site, derived from airborne lidar scans, with a 20m resolution.
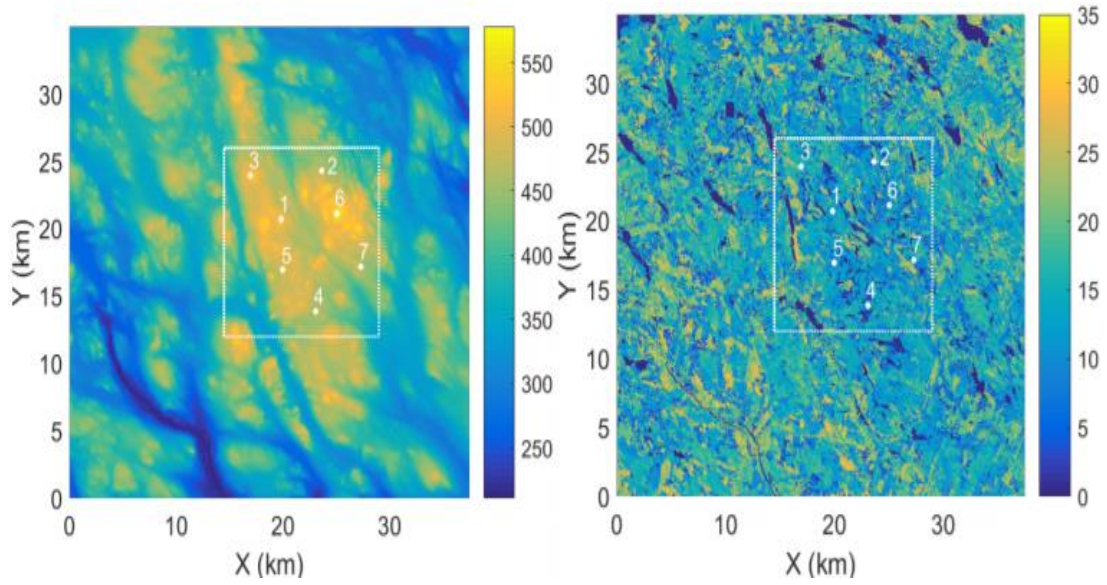
Figure 24 show the tree heights and elevation derived from the airborne laser scan processing, and an overview of the location of the seven meteorological masts applied in this study. From the tree height map, it can be seen that the area is heavily forested, but includes several clearings as well. This makes the site ideal for testing the different data input methods, as the meteorological masts are impacted by tree heights that range between 5 and 35 meters. The focus of this study is on the forest parameters, but the topography will also impact the results and change the forest's impact on the wind conditions, why a terrain including variability like the one introduced in Figure 24 is considered ideal for this study.

3.2.3.2   Converting forest height to roughness length and displacement height

While the aerial scans allow a reasonable approximation of the forest height, the WAsP flow model needs a roughness length term Z_0 for dealing with surface roughness. In this study the relatively simple conversion that was used by (Enevoldsen, 2016) has been slightly modified and utilized for converting directly between forest height and roughness length, as presented in (8)

(8)
$$z_0 = \begin{cases} 0.1 h_c & \text{for } h_c \geq 0.5 \\ 0.1 & \text{for } h_c \geq 0.5 \\ 0.0001 & \text{for water areas} \end{cases}$$

where h_c is the forest height as defined in the previous section. To simplify the maps and reduce the number of roughness changes such that the maps would be compatible with WAsP, the forest height map was rounded to the nearest 5 ~m height. This dataset is named the Optimized Roughness Approach (ORA) (Enevoldsen, 2016). In addition to the roughness lengths, the forest height was used to calculate a displacement height that was added to the topography. The displacement height provides the height where the wind speed reaches 0 m s^{-1}, which in forests is above the surface. Enevoldsen (2016) also provided a relationship between forest height and displacement height, which is used in this study, and presented in (9)

(9)
$$d = 0.66 * \text{tree height}$$

The displacement heights were added to the topography, providing a slightly modified surface for the WAsP modeling. The impact is presented in Table 21 with the displacement heights determined from pixels within a 50 m radius around each tower location for each of the laser based resolutions.

Table 21 The displacement heights determined from pixels within a 50 m radius around each meteorological mast location for each of the laser based resolutions

Approach	Mast 1	Mast 2	Mast 3	Mast 4	Mast 5	Mast 6	Mast 7
ORA20D	2.46	5.08	6.39	5.09	6.67	4.77	6.40
ORA100D	5.98	5.43	7.87	8.55	8.13	6.30	8.53
ORA500D	8.11	7.41	10.09	7.57	7.59	7.01	8.34
ORA1000D	7.91	7.98	9.89	7.11	7.38	7.05	9.27

3.2.3.3   *Down-resolving laser based forest heights*

One of the aims of this study was to test the importance of keeping a high degree of detail for the wind model predictions for forested sites. Therefore, it was important to evaluate the ORA dataset at several different resolutions, to determine if the added value of the laser data would carry over to coarser resolutions, or if the high resolution scans were necessary. The 20x20 meters resolution maps were downgraded to 100, 500 and 1000 meter resolutions by the following steps:

1. The forest height was re-calculated as the average of the forest height pixels in the higher resolution map.
2. Water areas were kept if the coarser resolution pixel consisted of more than 50% of high-resolution water pixels.
3. The new forest heights were converted to roughness length and displacement height as in (8) and (9)

Table 21 shows the displacement heights for each of the resolutions, here it can be seen that for most mast locations, the impact of the clearings on the displacement height is reduced at coarser resolutions. Figure 26c and 26d show the impact of the decreased resolution between the 100m and 500m ORA datasets, it can be seen that the water area is significantly reduced in ORA500, and that there are also fewer pixels with other low roughness values, but that the general patterns of the forest remain consistent.

3.2.3.4   *Conversion of raster maps to vector maps for WAsP*

The WAsP flow model currently can only work with vector based roughness and elevation maps. Therefore, the raster based maps produced by the above process need to be vectorized. This process was carried out using Version 11.20.5, Release D of the WAsP Map Editor. The Map Editor allows for the importing of raster based maps, which it then either contours, for elevation data, or converts to roughness change lines. For elevation data, the raster data is converted to equidistant contours, in this study we used 10 meters spacing for these contours. We also applied the same resolution (60 meters) for all elevation data in this study. For the roughness change lines, the map editor allows an option to keep the same roughness classes as in the raster file, and this is the option we chose. The map editor then outlines all of the pixels with roughness change lines that represent the inside and outside roughness value, skipping those where both sides of the line would be the same. After processing the data, they were examined via GIS to ensure that the vector data provided a reasonable representation of the elevation and roughness raster data.

3.2.3.5 *Roughness maps based on land use classes*

A common way of obtaining roughness information for wind flow modeling is through the conversion of land use classifications to roughness through lookup tables. In this study, four different sources of land use classifications are investigated. These four datasets are provided for download by EMD through their WindPro software. This is a common software used in wind flow modeling, and the availability of the maps for direct download makes them a commonly used source of map information. An overview of the products is presented in Table 22. These datasets represent land use over approximately two decades, and a number of different spatial resolutions. The wide range of spatial resolutions makes this collection ideal for comparisons with the different resolutions of the ORA dataset.

Table 22 Input data sources

Name	Spatial Resolution	Number of classifica-tions	Satellite Coverage	Reference
Corine land cover	100	44	2006	(EEA, 2007)
ESA GLOBCOVER	300	23	2009	(Bontemps, et al.,
Modis Vegetation Continuous Field	500	7	2001	(DiMiceli, et al.,
Global Land Cover Classification	1000	24	1992-	(Hansen, et al.,

All four of the land cover datasets used in this study were derived from satellite measurements, however there are some significant differences. The CORINE dataset only covers Europe, but has been used fairly extensively in mesoscale meteorological modeling (Pindea, et al., 2002), due to its high spatial resolution and large number of classification classes. Of the 44 classifications in the CORINE dataset, five are associated with forests. The GLOBCOVER data has been used in larger projects such as the Global Wind Atlas and while it has a lower resolution than the CORINE data, it is a more recent dataset, provides global coverage, and important for this study has 8 forest classes out of the 23 different land cover classifications. The MODIS Vegetation Continuous Field is not a true land cover dataset. Instead it provides information about three components of the ground cover: percentage of tree cover, percentage of non-tree vegetation, and percentage of bare ground (Carroll, et al., 2010). Finally, the GLCC dataset provides a coarse resolution land cover dataset to compare with the coarser resolutions of the ORA dataset.

3.2.4 WAsP model setup

WAsP version 11.6 was used in this study to compute the wind speeds and power density at the different masts. This model allows for the simulation of a wind climate at a new location using an observed wind climate. This is done through identifying differences in roughness and elevation at the different locations. The effect of changes in roughness length around the site are modeled using the internal boundary layer zooming-grid (IBZ) model (Petersen, et al., 1989; Sempreviva, et al., 1990), while the speed-up effects from terrain elevation are simulated using the spectral model described in (Troen & De Baas, 1987). Maps of the elevation and roughness length and an observed wind climate are needed to perform a WAsP model run. Correction factors are applied to the Weibull A parameter for each sector to correct for the impact of varying roughness. For computational efficiency, an algorithm is used that finds the number n out of k total roughness changes that are most important for

each sector. This is done by log-transforming the roughness values and using an exponential decay for the distance to the roughness changes x following (10)

(10)
$$x = x_d \left[1 - \exp(\frac{-x_k}{x_d}) \right]$$

where x_d is a decay length, which currently is set to 10 km. Then, a step function is fitted to another step function with all roughness changes, by either reaching the max number of allowed steps n_{max} or by getting below a specified threshold of residual variance RMS_{max}. The default values for n_{max} and RMS_{max} are 10 and 0.3, respectively. The WAsP model takes into account the effect of atmospheric stability by prescribing a long-term distribution of heat fluxes with a certain mean and spread. The mean and the standard deviation of the distribution of heat fluxes over land were set to -40 and 100 W m^{-2}, respectively. Over sea, these values were set to -8 and 30 W m^{-2}. It is unknown whether these values are realistic over the Swedish forest. Generally one would expect the long-term mean heat flux to be more negative at high latitudes, but due to the filtering steps applied in this research most of the data were obtained during summer. Therefore, it was decided that these values were reasonable.

Cross predictions are used to evaluate the model runs. A cross prediction is defined as the prediction of the flow from an observed wind climate at a certain mast and height to another one. For each cross prediction the WAsP modelling chain is applied. This modelling chain is extensively described in (Petersen, et al., 1989), but here we briefly repeat the steps:

1. Fit a Weibull distribution to each sector
2. Compute a generalized wind climate for 5 heights and 5 roughness lengths, by removing the effects of the roughness, terrain, and atmospheric stability at the observational site.
3. Apply the effects of roughness, terrain, and stability for the predicted site.

The predicted wind climate can be quite sensitive to the choice of the standard heights and roughness lengths in the generalization process. Mortensen (2016) found that errors in mean wind speed up to 1% can occur when the predicted height is not set equal to one of the generalized wind atlas heights. Therefore, to minimize errors that occur due to interpolation between the generalized heights, they were set to 3, 10, 30, 60 and 120 m above the surface. The standard roughness lengths were set to 0.0, 0.1, 0.4, 1.0, 3.0 m, which covers all possible roughness length values that occur in the maps. In the WAsP model, large water bodies are required to have a roughness length of 0.0 m, which are then internally converted to a value of z_0=0.0002.

Figure 25 Histogram of the observed wind speed U at mast 1 at 59 m agl. The red line denotes the Weibull distribution that the WAsP model
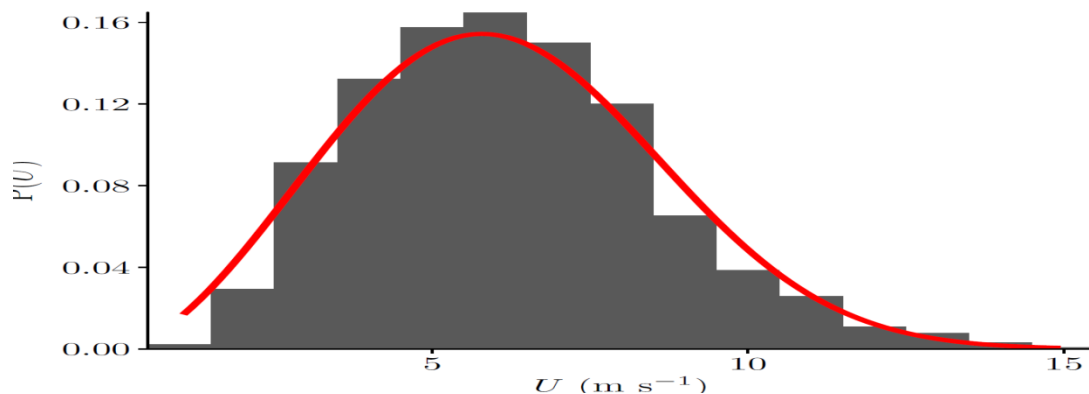
3.2.5   Results

The results of the analysis described in the three previous sections are described here. First the results of the wind data filtering algorithms will be shown. Then the results of the airborne laser scanned roughness lengths will be compared with the land cover based datasets. Finally, the results from the WAsP cross predictions will be shown.

3.2.5.1   ORA results

Figure 26 shows the roughness lengths of the four different land cover datasets and two resolutions of the ORA data.

Figure 26 Roughness maps, coloured by roughness value. Open circles show mast locations.
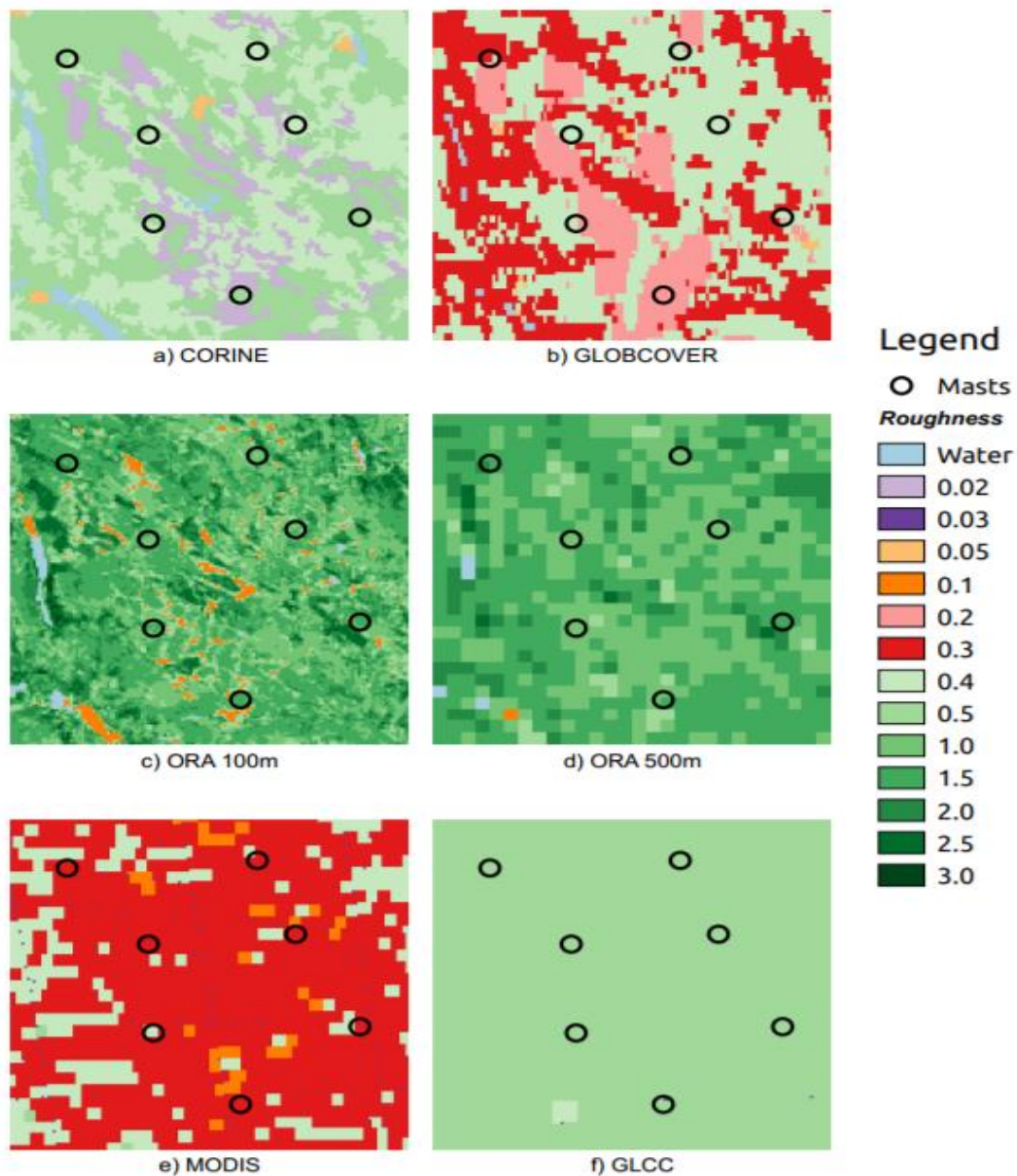
There are several key features seen in the different roughness maps. First, it can be seen that the small lakes in the eastern part of the domain are not well represented at resolutions of 500m or more. In addition to the different magnitudes, the forest edges and clearings are positioned differently across the different datasets, which can impact the output of resource assessment and the expected performance of a wind turbine (Enevoldsen, 2016). It is also clear that the roughness lengths from the two ORA datasets are four to six times greater than the roughness lengths from the online sources, and that the ORA data, due in part to the higher roughness values, has significantly more large roughness changes. For example, CORINE only has approximately two forest roughness lengths 0.4 and 0.5m, while the ORA data represents forest roughness lengths in 6 different bins from 0.5 to 3.0m. These features can be seen more clearly in a histogram of the roughness lengths from the same six datasets in Figure 27.

Figure 27 Histogram of roughness for different datasets over the same domain as shown in Figure 25
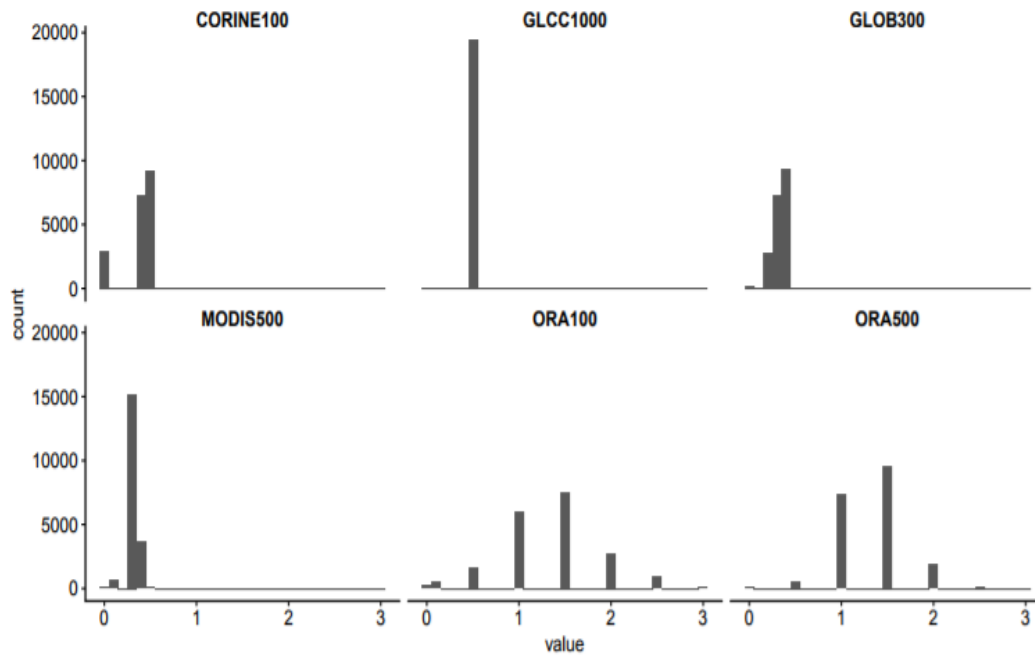
3.2.5.2   WAsP results

The following section introduces the WAsP results by comparing the different roughness approaches, and further investigating the impact of a range of configurations in the setup of the roughness models. Given that there are 702 cross predictions, summary charts are shown for evaluation of the different datasets. Figure 28 shows the mean absolute errors from all cross predictions. From this, it can be seen that the plots based on ORA all are closer to 0, and thereby have a smaller errors when compared to the land use based roughness lengths.

Figure 28 Absolute percent errors of the wind speed for each of the cross predictions. Colours denote the different roughness datasets, and the data is sorted on the x-axis from lowest error to highest error.
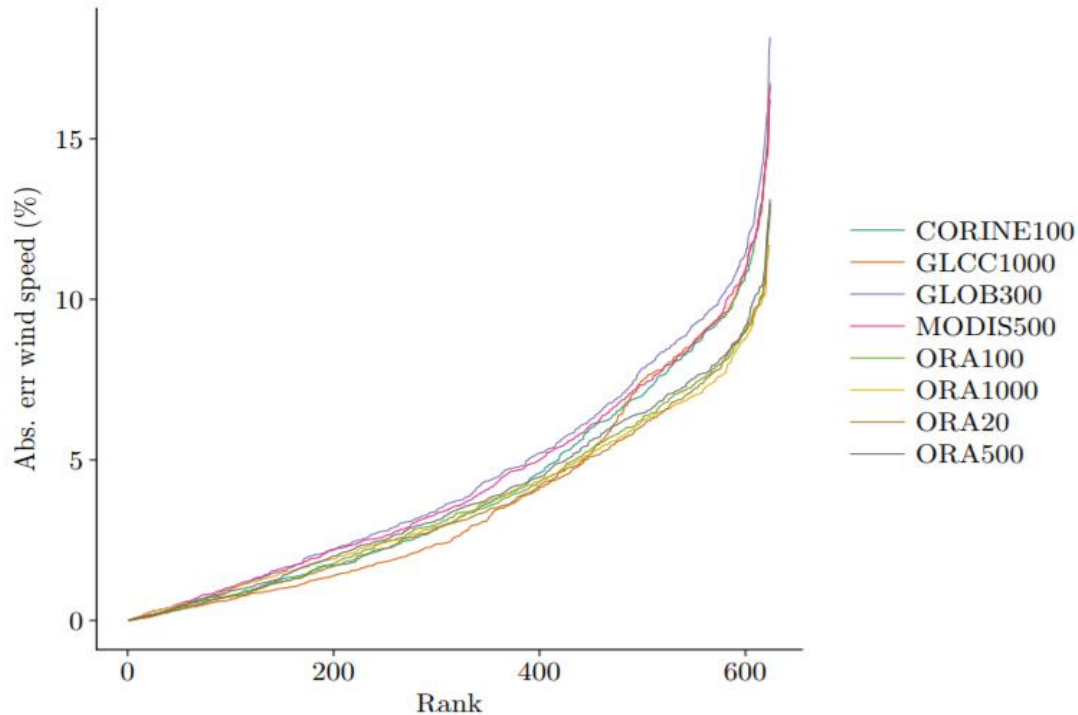
When comparing across different data sources in Figure 28, spatial resolution is not the key differentiator of performance, since all of the ORA resolutions provide better results than the land use based sources. Also for around 400 of the cross predictions, the GLCC1000 data, which has almost no roughness changes in the immediate vicinity of the masts performs best. However, when looking only at the different ORA resolutions themselves, a decrease in accuracy is found when the resolution decreases. The decreasing accuracy can be explained by fewer roughness changes obtained in the model, such as clearings or forest edges, which is no longer included in the map, due to the decreasing resolution. It can therefore be hypothesized that ORA provides better results because of both the higher mean roughness values, and the increased detail of the forest structure. In Figure 29 the results are presented for each mast, based on one cross prediction. The data has been normalized from mast 1 at the height of 59 meters, due to the quality of the measurement campaign and the cup anemometer. For this analysis only the highest resolution ORA data is shown, however the dataset was used twice, once with displacement heights included (ORA20D) and once without (ORA20).

Figure 29 The modelled mean wind profile (lines) and the observations (points) at the seven masts. All the profiles were obtained by using the observed wind climate from mast 1 at 59.0 m
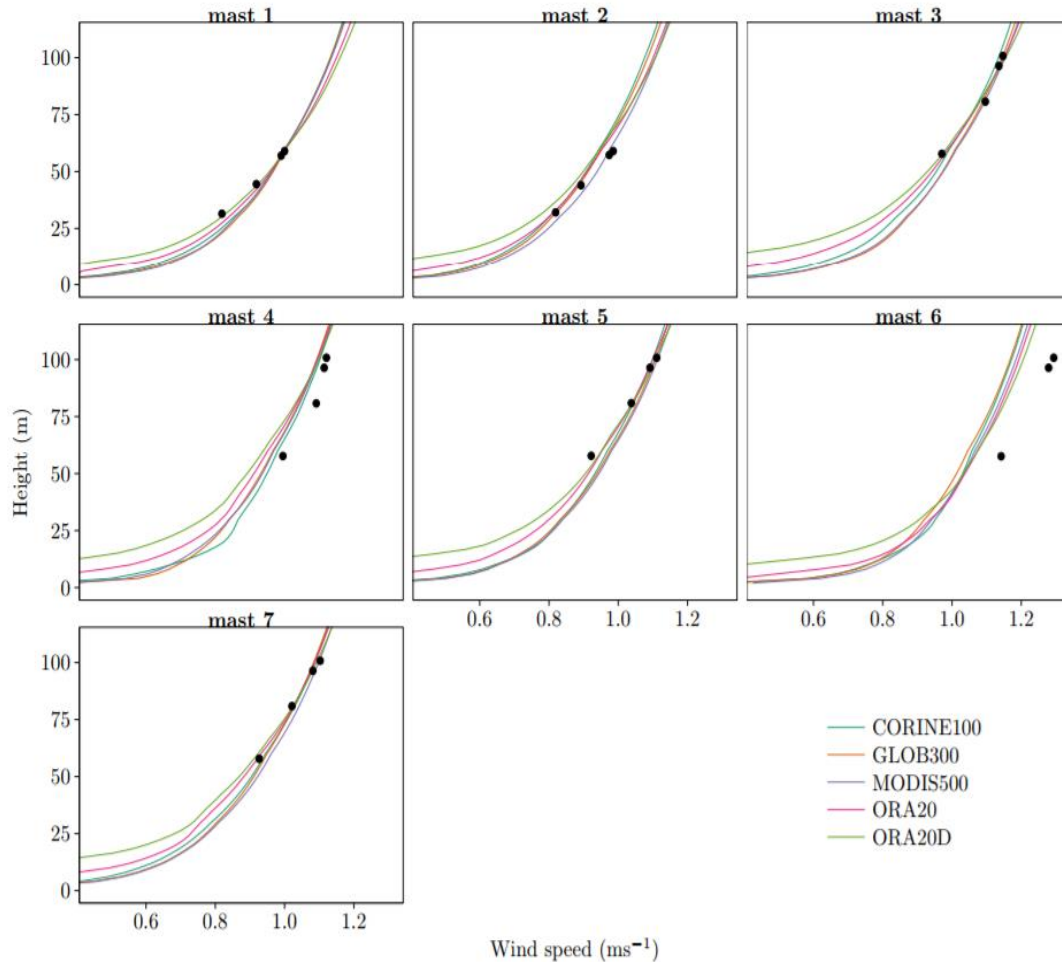
The impact of combining the roughness conversion with a displacement height factor can be observed in Figure 29. Here it can be seen that the displacement height has the largest impact at lower heights, however, at higher heights, the profiles align due to the decreased impact of the forest canopy.

Figure 30 shows the results from a sensitivity test of the WAsP roughness change selection algorithm described in this research. In these tests, the residual variance was reduced from its default value of 0.3 to 0.1. This has the effect of allowing more roughness change lines to be used in the IBZ model. This was done in part due to concern of oversaturating the roughness changes when high resolution roughness data was added to WAsP.

Figure 30 As Figure 28, but comparing the impact of including more roughness changes RMSmax = 0.1 than default, and including displacement height
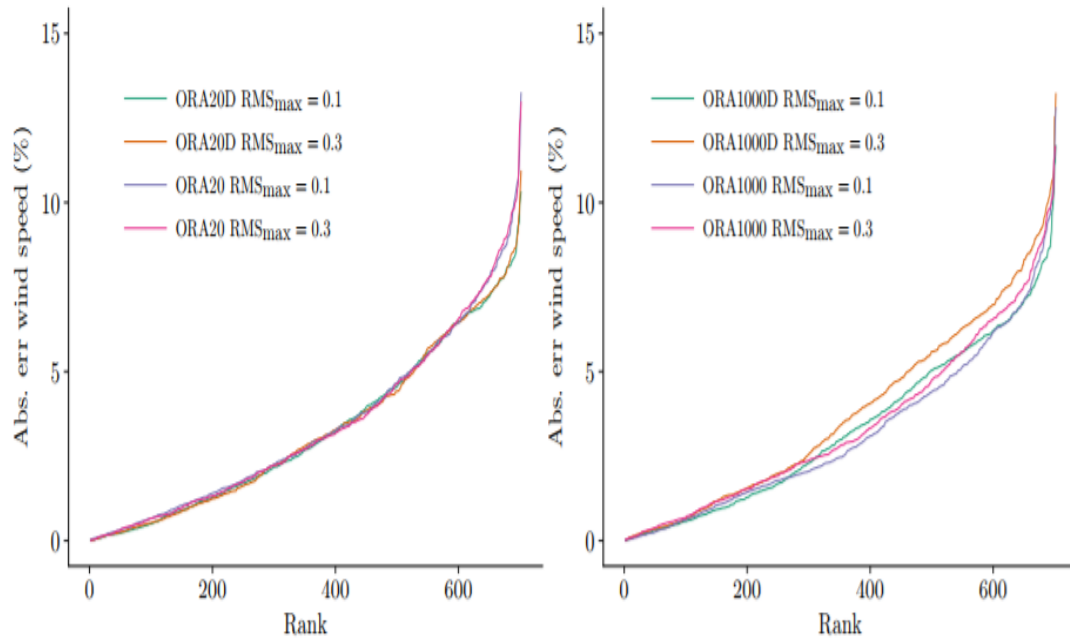
The left panel of Figure 30 shows the impact of the change for the highest resolution ORA data. Here, there is minimal difference in the model performance when more roughness change lines are used. However, the right panel shows the same analysis for the coarsest ORA resolution for which there were relatively large differences in the model result. It was found that running with a smaller RMS_{max} of 0.1, better results were obtained. This suggests that the inclusion of more roughness lines is more significant for the courser resolution data. Intuitively, this makes sense since the higher resolution data will have more roughness changes and therefore a larger amount of total roughness variance, which means that the residual variance will likely not be as sensitive of a number as the number of changes. However, for the coarser data, there will be fewer changes, and therefore each included change will account for more of the variance. Therefore, by reducing RMS_{max} more roughness changes will be included and the model will better simulate the changes in the flow due to roughness.

In addition to showing the impact of adding more roughness changes, the plot also shows the impact of including the displacement height on the model results. At 20 meters resolution, the inclusion of displacement heights reduces the highest error cross predictions by a significant amount, but for the majority of the cross predictions the results are comparable. At 1000 meters, however, the results are quite different. Here the simulation with displacement height performs significantly worse than the simulation that did not include it. From Table 21, it is found that the displacements for the 1000 meters case are significantly higher than those of the 20 meters case at all masts. This suggests that the displacement height is likely too high to represent the actual conditions at the mast. Therefore, it is recommended that the displacement height correction only be performed when detailed information about the displacement heights around the masts are known.

118

Finally, summary errors statistics of the results from the 702 cross predictions are shown in Table 23 In addition to the absolute percent error shown in Figure 28 and Figure 30, the additional error metrics mean bias and root mean square error (RMSE) have been included. The RMSE was calculated for both the mean wind speed U and the power density P predictions. P can be computed from the third moment of the Weibull distribution as (11)

$$(11) \qquad P = 0.5pA^3\Gamma(1 + \frac{3}{k})$$

where p is a reference air density (here 1.225 kg m^{-3}) It can be concluded that an error in A is cubed, showing that the power density errors are usually much higher than those in mean wind speed. (Kelly, et al., 2014) showed that errors in estimation of the k parameter of the Weibull distribution can result in large errors in P. In Table 23 it can be observed that the ORA100D has the lowest errors in power density, whereas the ORA20D has the lowest errors in U. The lowest value of an error metric is denoted in bold.

Table 23 Summary of the error metrics using all model runs (702 cross predictions)

Data Source	Mean bias (%)	Mean abs. error (%)	RMS error U (%)	RMS error P (%)
CORINE100	0.30	3.82	5.02	17.09
GLOB300	0.31	4.27	5.48	18.49
GLCC1000	0.51	3.62	4.92	17.13
MODIS500	0.22	4.10	5.21	17.35
ORA20	0.10	3.32	4.25	13.78
ORA100	0.16	3.42	4.34	14.02
ORA500	0.19	3.59	4.52	14.35
ORA1000	0.28	3.47	4.33	13.45
ORA20D	**0.07**	**3.22**	4.06	12.18
ORA100D	0.16	3.27	**4.03**	**11.61**
ORA500D	0.24	4.01	5.01	14.54
ORA1000D	0.33	3.84	4.78	14.06

Table 23 is defining y as modelled and x as observed variable with a line denoting a mean, the mean absolute relative error is defined as (12) the mean bias $\overline{y_i - x_i}$ and the root-mean-square error (RMSE) in percent of the wind speed U and the power P as (13).

$$(12) \qquad \overline{100(y_i - x_i)/x_i},$$

$$(13) \qquad \sqrt{\overline{(100(y_i - x_i)/x_i)^2}}.$$

For all metrics the high resolution ORA datasets, those with spacing less than 500m, provide better cross productions than all standard datasets. It is also observed that by increasing the spatial resolution, ORA based datasets provide lower errors. This separation is also seen when comparing the

displacement height results, where below 500m resolution ORA results improve with the inclusion of the displacement height, while above that resolution the results are worse. This suggests that there are features below 500m that are key to predicting the winds across these 7 masts when using the ORA datasets, which are not captured accurately for resolutions with grid spacing higher than this. However, this is not what is found for the standard roughness length datasets. In these datasets, the models perform similarly despite their different resolutions, with the coarser resolutions preforming better in all metrics except the RMSE of the power. In particular the GLOBCOVER dataset performs quite poorly despite having 300m resolution, only performing better than the GLCC data in terms of mean bias, and worst across the standard methods for all the other metrics. This highlights that resolution is not a panacea, but only improves performance when the resolution provides more accurate results. This is particularly interesting given the lack of roughness changes in the GLCC data.

In Table 23 the mean bias from all model runs is very close to zero. One would expect a difference between runs with a very low and very high roughness, for example the CORINE100 and ORA100 run. However, it can be seen that for both these runs, the bias is very close to zero. This is likely because we cross-predict both upwards and downwards. This results in errors that will cancel each other. For example, when there is a mean positive model bias due to a low roughness, this will result in an over prediction for an upward extrapolation, but in a under prediction for a downward extrapolation.

3.2.6   Conclusions

By examining wind conditions at seven meteorological masts in a forested area in Sweden, it can be concluded that tree height-based roughness maps resulted in a closer agreement with observational data compared to standard conversions from land use classes. It was discovered that the chosen approach, ORA, provided better results than online available roughness length maps despite lowering the spatial resolution to 1000 meters. It can therefore be derived that siting engineers and practitioners of wind resource assessments in forested areas should collect appropriate site data that describes the forest height – and type. It was furthermore discovered that roughness length maps with a high resolution can benefit significantly from applying a displacement height factor as described in ORA.

3.3 References

The following references were applied in the third journal article. (Based on the sequential order in the article).

Ackermann, T. & Söder, L., 2000. Wind energy technology and current status: a review. *Renewable and Sustainable Energy Reviews,* Volume 4 , pp. 315-374

Christie, D. & Bradley, M., 2012. Optimising land use for wind farms. *Energy for Sustainable Development ,* Volume 16 , p. 471–475.

Tabassum-Abbasi, Premalatha, M., Tasneem Abbasi, N. & Abbasi, S., 2014. Wind energy:Increasing deployment, rising environmental concerns. *Renewable and Sustainable Energy Reviews ,* Volume 31, pp. 270-288.

Global Wind Energy Council, 2013. *www.gwec.ne.* [Online]
Available at: http://www.gwec.net/global-Figures/wind-in-numbers/
[Accessed 20 September 2013].

Global Wind Energy Council, 2012. *Global Wind Report Annual market update 2012*

Bilgili, M., Yasar, A. & Simsek, E., 2010. Offshore wind power development in Europe and its comparison with onshore. *Renewable and Sustainable Energy Reviews,* Volume 15, pp. 905-915.

Sovacool, B., 2014. Energy Studies Need Social Science. *Nature ,* Volume 511 , pp. 529-530.

Sovacool, B., 2014. What Are We Doing Here? Analyzing Fifteen Years of Energy Scholarship and Proposing a Social Science Research Agenda. *Energy Research & Social Science*, Volume 1, pp. 1-29.

Aitken, M., 2010. Why we still don't understand the social aspects of windpower:A critique of key assumptions within the literature. *Energy Policy,* Volume 38, p. 1834–1841

IEA, 2012. *Medium-term renewable energy market*

Wilkes, J. & Moccia, J., 2013. Wind in power 2012 European statistics, *The European Wind energy association.*

Nadaï, A. & Labussière, O., 2009. Wind power planning in France (Aveyron), from state regulation to local planning. *Land Use Policy*, Volume 26, pp. 744-754.

Huberta, T. & Vidalenc, E., 2012. Renewable Electricity Potentials in France: A Long Term Perspective. *Energy Procedia,* Volume 20, pp. 247-257.

Szarka, J., 2007. Why is there no wind rush in France?. *European Environment*, Volume 17, pp. 321-333..

Jones, C., 2006. Vive LA wind: Fair blows the wind for France?. *Refocus,* Volume 7, pp. 36-38.

Nadaii, A., 2007. ''Planning'', ''siting'' and the local acceptance of wind power: Some lessons from the French case. *Energy Policy*, Volume 2, p. 2715–2726.

Roques, F., Hiroux, C. & Saguan, M., 2010. Optimal wind power deployment in Europe—A portfolio approach. *Energy Policy,* Volume 38, p. 3245–3256

IEA, 2010. Energy Policies of IEA Countries: France 2009 Review. *International Energy Agency.*

Jobert, A., Laborgne, P. & Mimler, S., 2007. Local acceptance of wind energy: Factors of success identified in French and German case studies. *Energy Policy*, Volume 35, p. 2751–2760.

Nadaï, A. & van der Horst, D., 2010. Wind Power Planning, landscapes and publics. *Land Use Policy*, Volume 27, pp. 181 - 184.

Körmendi, E., Egsmose, L. & Noordhoek, J., 1986. Datakvalitet ved telefoninterview. 1st ed.: *Socialforskningsinstituttet*.

Nielsen, P., 2002. Case studies calculating wind farm production. 1 ed.: *Energi- og Miljødata.*

Wizelius, T., 2007. Developing Wind Power Projects. 1st ed.: *Earthscan*.

Manwell, J., McGowan, J. & Rogers, A., 2009. Wind Energy Explained: Theory, Design and Application. 2nd ed:*Wiley*.

Hellström, M., 1998. Vindkraft i Harmoni: *Energimyndigheten*.

Sovacool, B., Sidortsov, R. & Jones, B., 2014. Energy Security, Equality, and Justice.: *Routledge*.

Greenberg, M. R., 2014. Energy policy and research: The underappreciation of trust. *Energy Research & Social Science*, Volume 1, pp. 152-160.

Sovacool, B. K. & Ratan, P. L., 2012. Conceptualizing the acceptance of wind and solar electricity. *Renewable and Sustainable Energy Reviews*, Volume 16, p. 5268–5279.

Wustenhagen, R., Wolsink, M. & Burer, M. J., 2007. Social Acceptance of Renewable Energy Innovation: An Introduction to the Concept. *Energy Policy* , Volume 35, pp. 2683-2691.

Sovacool, B., 2009. Exploring and Contextualizing Public Opposition to Renewable Electricity in the United States. *Sustainability*, Volume 1, pp. 702-721.

Breukers, S. & Wolsink, M., 2007. Wind Power implementation in changing institutional landscapes: An international comparison. *Energy Policy*, Volume 35, pp. 2737-2750.

Bolsen, T. & Cook, F., 2008. Public opinion on energy policy: 1974-2006.. *Public Opin. Quart*., Volume 72, pp. 364-388.

Devine-Wright, P., 2005. Beyond NIMBYism: towards an Integrated Framework for Understanding Public Perceptions of Wind Energy. *Wind Energy* , Volume 8, pp. 125-139.

Bell, D., Gray, T. & Haggett, C., 2005. The social gap in wind farm siting decisions: Explanations and policy responses.. *Environ. Polit.* , Volume 14, pp. 460-477.

Walker, G., 1995. Renewable energy and the public.. *Land Use Policy*, Volume 12, pp. 49-59.

Krohn, S. & Damborg, S., 1999. On public attitudes towards wind power. *Renewable Energy*, Volume 16, pp. 954-960.

Hirsh, R. & Sovacool., B., 2013. Wind Turbines and Invisible Technology: Unarticulated Reasons for Local Opposition to Wind Energy. *Technology & Culture*, Volume 54, pp. 705-734.

Warren, C., Lumsden, C., O'dowd, S. & Birnie, R., 2005. 'Green on Green': Public perceptions of wind power in Scotland and Ireland. *Journal of Environmental Planning and Environment* , Volume 46, pp. 853-875.

S., A. & Konisky, D., 2009. Public attitudes toward construction of new power plants.. *Publi Opin. Quart.*, Volume 73, pp. 566-577.

Wolsink, M., 2000. Wind power and the NIMBY-myth: Institutional capacity and the limited significance of public support. *Renewable Energy* , Volume 21, pp. 49-64.

Wolsink, M., 2007. Wind Power implementation: The nature of public attitudes, equity and fairness instead of backyard motives. *Renew. Sustain. Energ. Rev*., Volume 11, pp. 1188-1207.

Kempton, W. et al., 2005. The offshore wind power debate: views from Cape Cod. *Coast Manage*, Volume 33, p. 119–149.

Petrova, M., 2013. NIMBYism revisited: public acceptance of wind energy in the United States. *WIREs Clim Change* , Volume 4, p. 575–601.

Saidur, R., Rahim, N., Islam, M. & Solangi, K., 2011. Environmental impact of wind energy. *Renew Sustain Energy Rev*, Volume 15, p. 2423–2430.

Magoha, P., 2002. Environmental impacts of wind power. Footprints in the wind?.

Bright, J. et al., 2008. Map of bird sensitivities to wind farms in Scotland: A tool to aid planning and conservation. *Biological Conservation*, Volume 141, pp. 2342-2356.

Chiras, D., Sagrillo, M. & Woofenden, I., 2009. Power from the Wind: Achieving Energy Independence. 1st ed.: *New Society Publishers* .

Ladenburg, J. & Dubgaard, A., 2007. Willingness to pay for reduced visual disamenities. *Energy Policy,* Volume 35, pp. 4059-4071.

Warren, C. R. & McFadyen, M., 2010. Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. *Land Use Policy*, Volume 27, pp. 204 - 213.

Troen, I. & Petersen, E. L., 1989. European Wind Atlas. 1st ed..:*Risø*.

Régnier, Y., 2010. http://www.100-res-communities.eu/communities/best-practices/montdidier-fr-pilot-town-in-energy-saving. [Online]
[Accessed 10 August 2014].

Khan, J., 2003. Wind power planning in three Swedish municipalities. *Journal of Environmental Planning and Management,* Volume 46, pp. 563-581

Neuhoff, K., 2005. Large scale deployment of renewables for electricity generation. *Oxford Review of Economic Policy ,* Volume 21, pp. 88-110.

Pettersson, F. & Söderholm, P., 2009. The diffusion of renewable electricity in the presence of climate policy and technology learning: the case of Sweden. *Renewable and Sustainable Energy Reviews,*Volume 13, pp. 2031-40.

The following references were applied in the fourth journal article.

Arnqvist, J., Segalini, A., Dellwik, E. & Bergström, H., 2015. Wind Statistics from a Forested Landscape. Boundary-Layer Meteorology, Volume 156, p. 53–71.

Baldocchi, D. &. M. T., 1988. Turbulence structure in a deciduous forest. Boundary-Layer Meteorol , Volume 43, p. 345–364.

Bergström, H. et al., 2013. Wind power in forests, s.l.: Elforsk.

Bontemps, S. et al., 2011. GLOBCOVER 2009 Products Description and Validation Report, s.l.: UCLouvain & ESA .

Boudreault, L.-E.et al., 2015. A LiDAR method of canopy structure retrieval for wind modeling of heterogeneous forests.. Agricultural and Forest Meteorology, Volume 201, pp. 86-97.

Carroll, M. et al., 2010. MODIS Vegetative Cover Conversion and Vegetation Continuous Fields, in: Land Remote Sensing and Global Environmental Change, edited by B., R., Justice, C., and Abrams, M.,. Springer, New York, p. 725–745.

Dellwik, E., Bingöl, F. & Mann, J., 2014. Flow distortion at a dense forest edge. Quarterly Journal of the Royal Meteorological Society, Volume 140, p. 676–86..

Dellwik, E., Jensen, N. & Landberg, L., 2006. Wasp in the forest.. Wind Energy.

DiMiceli, C. et al., 2011. Global land cover facility. [Online]

Available at: http://glcf.umd.edu/data/vcf/

[Accessed 8 October 2016].

EEA, 2007. CLC2006 technical guidelines, Tech. Rep. 17/2007, Copenhagen: European Environmental Agency.

Enevoldsen, P., 2016. Onshore wind energy in Northern European forests: Reviewing the risks.

Renewable & Sustainable Energy Reviews, Volume 60, p. 1251–1262.

Enevoldsen, P., 2016. Wind Power in Forested Areas:Determining the Roughness Length and Displacement Height for Coniferous Trees. New Orleans, s.n.

Enevoldsen, P. & Valentine, S. V., 2016. Do onshore and offshore wind farm development patterns differ?. Energy for Sustainable Development, Volume 35, pp. 41-51.

Hansen, M. C., Defries, R., Townshend, J. R. G. & Sohlberg, R., 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. International Journal of Remote Sensing, Volume 21, p. 1331–1364.

Hicks, B. B., Hyson, P. & Moore, C. J., 1975. A Study of Eddy Fluxes Over a Forest. Journal of Applied Meteorology , Volume 14.

Hui, S.-Y. & Crockford, A., 2008. Wind Profiles and Forests, Brussels: EWEC.

Jarvis, P. G., James, G. B. & Landsberg, J. J., 1976. Coniferous Forest. Vegetation and the Atmosphere, Volume 2, pp. 171-240.

Kelly, M., Troen, I. & Jørgensen, H. E., 2014. Weibull-k Revisited: "Tall" Profiles and Height Variation of Wind Statistics. Boundary-Layer Meteorology, Volume 152, p. 107–124.

Mortensen, N. G., 2016. Wind resource assessment using the WAsP software, Roskilde: Technical University of Denmark.

Mölder, M., Lindroth, A. & Grelle, A., 1999. Experimental Determination of the Roughness Length for Temperature Over a Field of Tall Grass in Central Sweden. Geografiska Annaler: Series A, Physical Geography, Volume 81, p. 87–100.

Patton, E. G. & Finnigan, J. J., 2012. Canopy turbulence. Handbook of Environmental Fluid Dynamics, Volume 1, pp. 311-328.

Petersen, E. L., Troen, I. & Mortensen, N. G., 1989. Europæisk vind atlas.. Vejret, Volume 39, pp. 37-41.

Pindea, N., Jorba, O., Jorge, J. & Baldasano, 2002. Using NOAA-AVHRR and SPOT-VGT data to estimate surface parameters : application to a mesoscale meteorological model. 1st International Symposium on Recent Advances in Quantitative Remote Sensing, Volume 1161, p. 16–20.

Raupach, M. R., 1994. Simplified Expressions for Vegetation Roughness Length. Boundary-Layer Meteorology, Volume 71, pp. 211-216 .

Raupach, M. R., 1995. Corrigenda. Boundary-Layer Meteorology, Volume 76, p. 303.

Raupach, M. R. & Thom, A., 1981. Turbulence in and above Plant Canopies.. Annual Review of Fluid Mechanics , Volume 13, pp. 97-129.

Sempreviva, A. M., Larsen, S. E., Mortensen, N. G. & Troen, I., 1990. Response of neutral boundary layers to changes of roughness. Boundary Layer Meteorology , Volume 50, p. 205–225.

Sogachev, A. & Panferov, O., 2006. Modification of Two-Equation Models to Account for Plant Drag. Boundary-Layer Meteorology, Volume 121, p. 229–266.

Troen, I. & De Baas, A., 1987. A Spectral Diagnostic Model for Wind Flow Simulation in Complex Terrain, edited by Palz, W. and Sesto, E. EWEC'86 Proceedings, Volume 1, pp. 243-249.

4 What is the best approach of managing the risks of wind project development in Northern European forests?

The fourth chapter seeks to demonstrate the usage of the findings from the previous chapters by placing methods and knowledge on risks associated with wind projects in forested areas in relation to implementable methods. The two journal articles used to answer the third research questions are presented below.

5. *A Socio-Technical Framework for Examining the Consequences of Deforestation: A Case Study of Wind Project Development in Northern Europe.* Submitted to Energy Policy.

6. *Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden. /Enevoldsen, Peter; Perminen, Finn. 2017.* Submitted to Renewable Energy Focus.

4.1 A Socio-Technical Framework for Examining the Consequences of Deforestation: A Case Study of Wind Project Development in Northern Europe

Wind projects are frequently developed in forested areas, and especially in Northern Europe, due to less restrictions and social opposition, favorable renewable energy policies and, of course, the heavily forested areas in this region of the world. Wind project development in forested areas has an unpreventable impact on nature, namely deforestation. The felling of trees is carried out to free space for the wind turbine installation and potentially also to increase the performance of the wind turbine and lower the levelized cost of energy. This study examines the impact of such a felling strategy, including the environmental and social consequences of deforestation. Based on a case study carried out in Sweden, this research study develops the first socio-technical framework for examining the consequences of deforestation. The deliverables of this research include recommendations for wind industry and forest industry stakeholders on how to apply deforestation in future development of wind projects in forested areas in Northern Europe. In addition, the framework is expected to encourage academia to further develop and analyze the socio-technical parameters associated with wind project development in forested areas.

4.1.1   Introduction

Onshore wind power has been recognized as a key technology in the transition towards a world powered by renewables (Jacobson, et al., 2017) and thus constitutes an important part of the various strategies employed in the battle against global climate change (Valentine, 2015; Rogelj et al., 2016). The political focus on and support for onshore wind power have resulted in an increase in the global installed onshore wind capacity with wind farms spread all over the globe. The wind power development in Northern Europe has been supported by feed-in tariffs, support schemes, and a strong, growing wind industry (Enevoldsen, 2016), and as Figure 31 clearly indicates, the UK, Sweden, Denmark, Finland, and Norway have seen a rapid growth in the development of onshore wind power.

Figure 31 Development in installed wind power capacity in Northern Europe (MW) (Global Wind Energy Council, 2016)
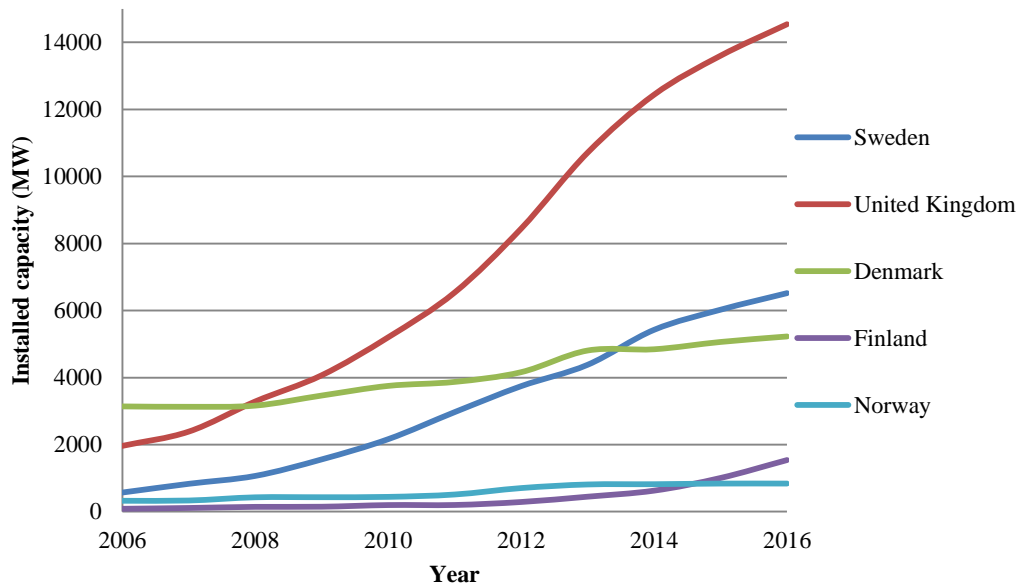
The rapid increase in onshore wind farm installations has led to a decrease in the number of suitable sites, increased social opposition (Enevoldsen & Sovacool, 2016; Ek & Persson, 2014), and increased land costs (Enevoldsen, 2016). In response to these factors and because wind turbines have increased remarkably in size (Enevoldsen & Valentine, 2016), it has become possible to deploy wind turbines in forested areas. The Northern European countries are heavily forested, and these forests are often located in rural areas (Enevoldsen & Valentine, 2016). This means that land acquisition may be cheaper and that the noise and flicker impact on humans is virtually non-existing, reducing the barriers to new wind project development. The percentage of each country's total land area covered by forest is shown in Table 24 below.

Table 24 Forest coverage for the Northern European countries (Enevoldsen, 2016; Finnish Forest Association, 2016)

Country	Forested land area (%)	Coverage of dominant tree types (%)
Denmark	13.5%	Abies alba and Picea abies 40.4%
		Various deciduous tree types 39.5%
Norway	38%	Picea abies 47%
		Pinus sylvestris 33%
Sweden	66%	Picea abies 42%
		Pinus sylvestris 39%
Finland	75%	Picea abies 50%
		Pinus sylvestris 46%
UK	12%	Picea sitchensis 29%
		Pinus sylvestris 17%
		Various deciduous tree types 40.2%

Table 24 indicates that these countries are heavily dominated by Norwegian spruce (Picea abies) and Scots pine (Pinus sylvestris). Both are categorized as coniferous evergreens, meaning that they do not shed their leaves in winter.

Despite the increased size of wind turbines, the forests are still causing changes in the wind flows, which make it challenging to estimate the wind conditions above the forest canopy. The increasing turbulence intensity and changes in the logarithmic wind profile have been studied intensively for decades, but only recently with a special focus on the trees' impact on a wind turbine's performance (Bergström, et al., 2013). A range of methods varying from determining the roughness length of trees based on observed tree heights (Enevoldsen, 2016) to determining the leaf area density from airborne laser scans (Dellwik, et al., 2016) has been developed to estimate the wind flows in and above the forest canopy in all lower boundary layer heights. Researchers agree that the impact of forest edges is the most severe in terms of changes in turbulence intensity and wind shear (Arnqvist, 2013; Dellwik et al., 2014). Furthermore, there is broad consensus between academia and the wind industry that the drag and roughness from the forests are slowing down the wind speed (Enevoldsen, 2016). Due to the two factors mentioned above, wind project developers often seek to cut down enough forest to avoid any severe impact on the mean wind speed, while ensuring that no forest edge effects occur near the wind turbines. The intention is to increase the annual energy production and simultaneously ensure a longer lifetime of the wind turbines, which conclusively impacts the return on investment and thus the levelized cost of wind energy. However, deforestation has also been identified as one of the primary reasons for social opposition to wind projects in forested areas (Enevoldsen & Sovacool, 2016). The arguments are either based on locals' perceptions of forests as areas for hiking, picnics, or joyful memories with kids and/or the irony of felling trees to install a technology to limit the emission of greenhouse gases and curb global climate change. The second argument is noteworthy, as the estimated CO_2 loss of felling one km^2 of Norwegian spruce and Scots pine is 248,276 ton. A wind farm of 20 wind turbines with rotor diameters of 100 m usually has 0.22 km^2 (Enevoldsen & Valentine, 2016) of space between each turbine, which, compared to deforestation, would equal an estimated CO_2 loss of 54,708 ton for a mix of Norwegian spruce and Scots pine[3] for each wind turbine. In addition, the felling of trees comes with a cost but also a potential income from timber or bio pallets, which can be included in the return on investment and the levelized cost of energy.

This research first suggests a literature-based, socio-technical framework for examining the impact of deforestation on a wind project. Subsequently, experiments were carried out for each of the parameters introduced in the framework in an effort to a) disclose whether deforestation is a necessary method for continuing the development of installed onshore wind power, b) potentially determine how much deforestation is needed, and c) potentially lend credence to the socio-technical framework as a sound method for investigating wind projects in forested areas.

4.1.2   Research materials and methods

The socio-technical framework is based on findings from an extensive literature review, which was carried out using a detailed search strategy that took into account the fact that the required interdisciplinarity of the study would demand a large number of articles. In Google Scholar and ScienceDirect, I used the following search words: "Wind power" and "forest" in combination with

---

[3] Estimated using http://informatics.sepa.org.uk/CarbonCalculator/.

"Northern Europe", "resource assessment", "social acceptance", "deforestation", "turbine performance", "Denmark", "Sweden", "Norway", "Finland", "United Kingdom", or "UK". The result was an astonishing number of more than 1,000 peer-reviewed papers. Next, a screening process was conducted to filter the number of papers, while applying the snowball technique to reveal any other relevant studies. The final number of peer-reviewed articles applied to analyze the framework tallied at 29, with a clear overweight of articles related to estimations of wind conditions. The number of articles for each parameter in the socio-technical framework is depicted in Figure 32 below.

Figure 32 Applied literature
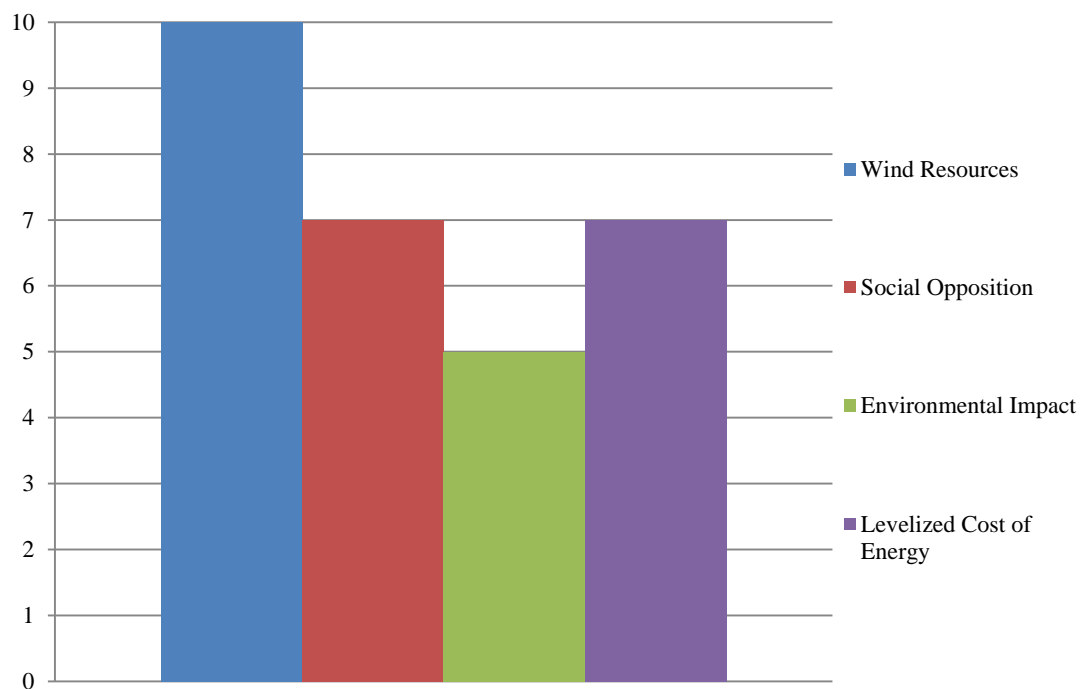
A country-specific search was applied, as the consequences of deforestation may vary depending on the global location. However, papers targeting other countries or non-defined locations were included in the study, if similarities and findings related to the Northern European countries were revealed.

4.1.2.1   *The beta version of the socio-technical framework*

The socio-technical framework presents the expected impact of deforestation in relation to development of wind projects. It is based on previous studies targeting the included parameters of the socio-technical framework. The framework is introduced in Table 25 below, including the references applied for the construction of each expected consequence.

<div align="center">Table 25 The beta version of the socio-technical framework</div>

Parameter	Expected consequences of deforestation	References
Wind resources	As forest is removed, increased wind speeds with lower turbulence are expected. This consequence is assumed to follow a somewhat linearized curve as a function of the increased deforested area.	(Gardiner, 2004; Bergström et al., 2013)
Social opposition	Increased social opposition due to the expected negative impact on flora, animals, and avian	(Enevoldsen & Sovacool, 2016)
Environmental impact	Increased CO_2 savings despite the deforestation owing to the increased annual energy production of the wind turbine.	(Perks, et al., 2010)
Levelized cost of energy	If timber can be sold from the deforestation, the increased annual energy production and income from timber are expected to result in lower levelized cost of energy after deforestation.	(Perks et al., 2010; Enevoldsen, 2016)

The four parameters introduced in the framework have been chosen as they all impact the possibilities of future growth and development of the installed capacity of wind power in Northern Europe.

Table 26, which introduces the methods applied to test the socio-technical framework, clearly indicates the need for an interdisciplinary research strategy. The research strategy is inspired by Sovacool (2014) who suggested that engineering needs social science, something which is expected to have been left out in many of the previously developed projects in Northern Europe. The interdisciplinary framework suggested in this study combines perspectives across different scientific paradigms. This mixed methods design allows to triangulate findings, thereby strengthening the framework, and serves as a broad tool applicable for several stakeholders in the wind industry.

Table 26 Research methods and materials

Parameter	Research method	Data collection	Test materials
Wind resources	Quantitative comparison of estimated annual energy production	Simulations are carried out using different forested scenarios with different sizes of deforestation from five operating wind projects	WAsP, QGIS, tree heights, elevation map, power curve, wind data
Social opposition	Qualitative	Semi-structured interviews conducted with eight wind project stakeholders	Structured questions
Environmental impact	Quantitative	Calculations of different deforestation scenarios	Annual energy production vs. estimated CO_2 loss
Levelized cost of energy	Quantitative	Calculations of different deforestation scenarios	Annual energy production + income – cost of deforestation

The literature applied in the construction of the socio-technical framework will be used in the analyses and discussions related to the tests carried out to examine in depth each framework parameter.

4.1.2.2 Wind resources

In order to examine the expected consequences of deforestation's impact on wind resources, a test has been carried out. The test simulates the changes in wind conditions according to whether the clear felling area surrounding a wind turbine is approx. 0, 1, 5, 12, or 23 hectares. The test was carried out at a real operating site in the central, heavily forested part of Sweden. The elevation and tree heights are presented in Figure 33 and 34 below, which uses the output from a national airborne laser scan presented in a grid with a spatial resolution of 20x20 meters.

Figure 33 Tree heights
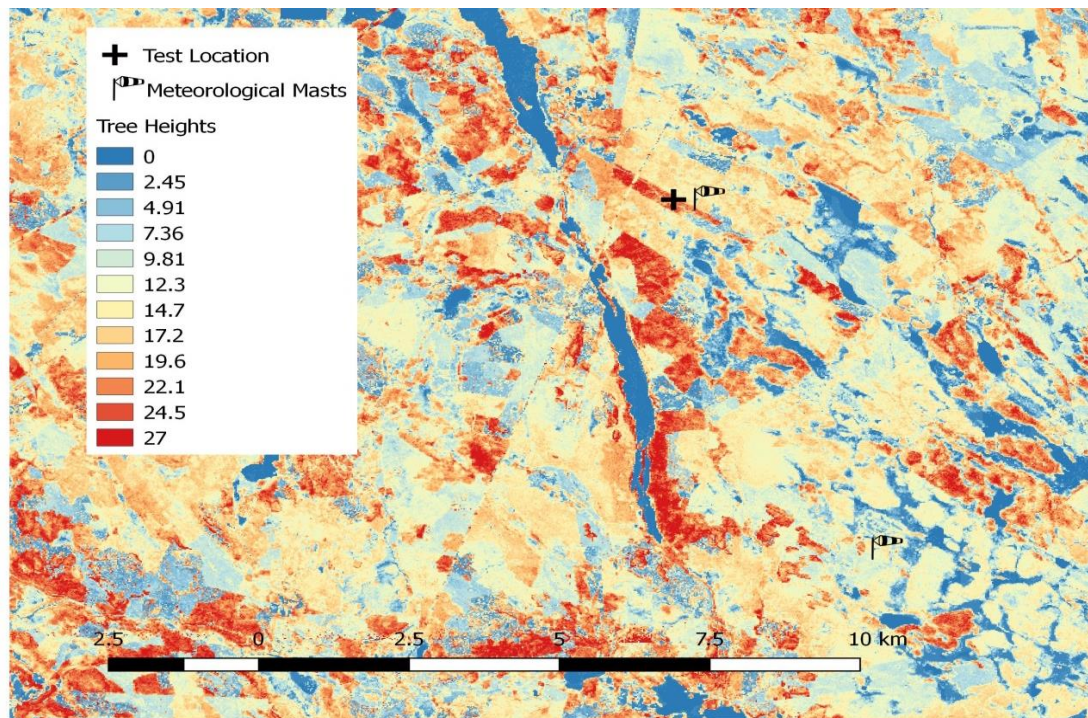
Figure 34 Tree heights
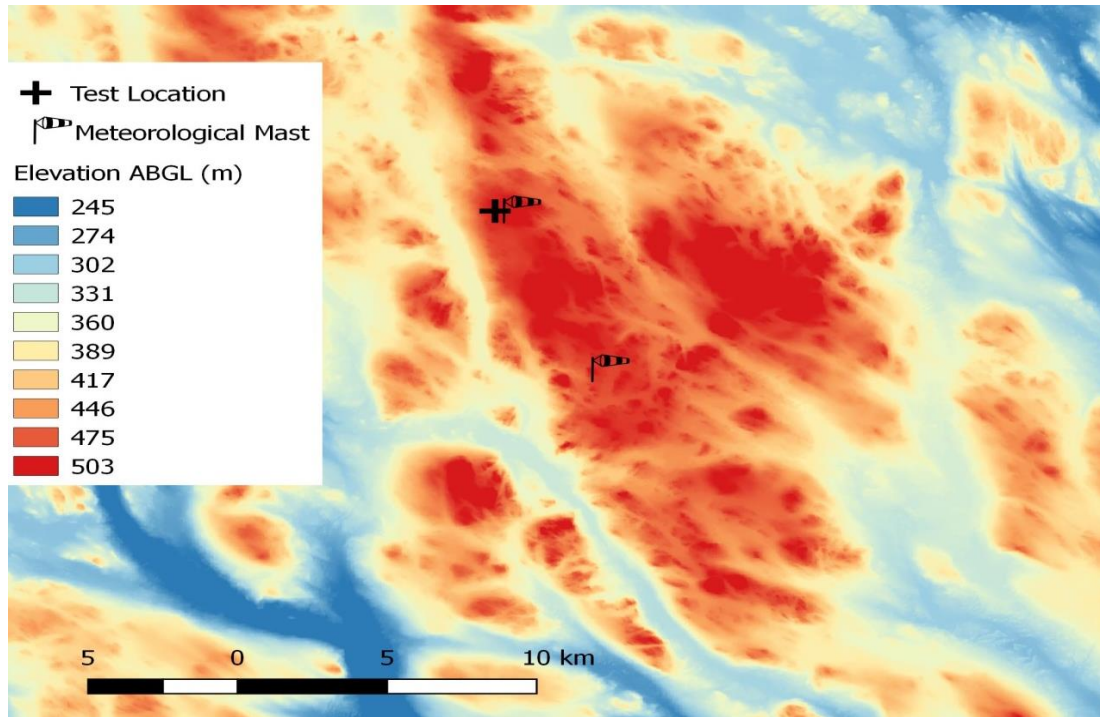
As illustrated in Figure 32, the area is heavily forested with many different tree heights represented on site. Furthermore, the location of the two meteorological masts used to verify the simulation approach is depicted, as is a black cross, which represents the test location. Figure 33 shows the elevation changes in the area, where minor inclinations are revealed. However, the altitude above sea level is more or less the same at the meteorological masts and the test location, which is why a linearized solver is considered sufficient for conducting the resource assessments.

4.1.2.3   Simulation approach

The simulation is carried out applying the Optimized Roughness Approach (ORA) introduced by Enevoldsen (2016), and it was verified by measurements from more than 30 forested areas. It applies a combination of roughness lengths of (14) from Hicks et al. (1975)

(14) $$Z_0 = 0.3 \cdot (tree\ height - Z_d)$$

and displacement heights from Garratt (1992) presented in (15)

(15) $$(Z_d)\ of\ Z_d = 0.66 * tree\ height$$

The calculations were performed using a combination of the ORA and the Wind Atlas Analysis and Application Program (WAsP) (WAsP, 2017). WAsP was applied, since no RIX factor was observed

above 1 and because it has been applied for wind simulations in forests in several cases (Dellwik et al., 2006; Raftery et al., 2004).

In this research, the approach of combining ORA and WAsP is applied for the scenarios presented in Figure 35 below. As indicated earlier, the scenarios range from 1 to 23 hectares of deforestation, which is compared to a baseline of no felling in the area.

Figure 35 Mapping the four scenarios
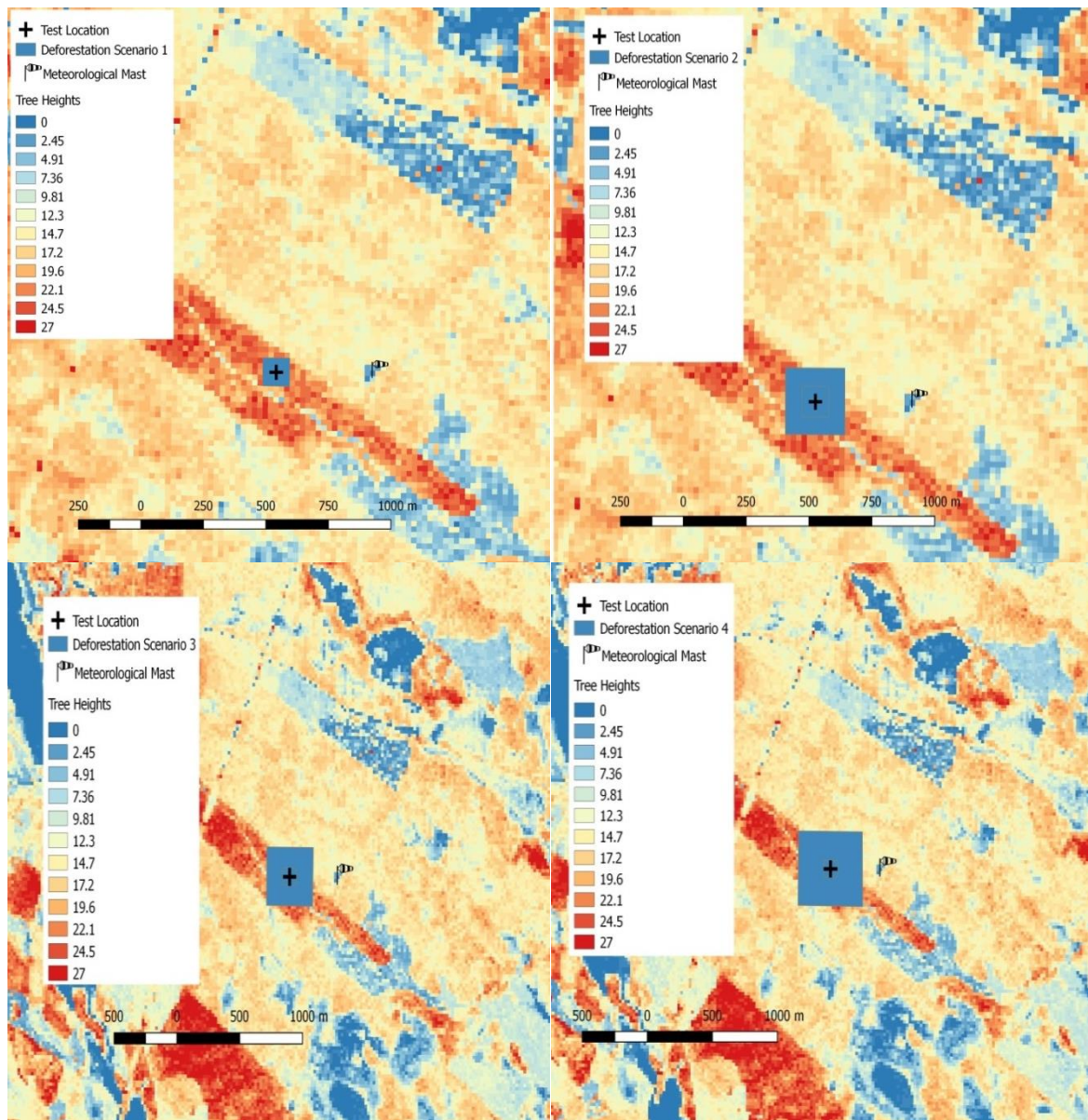
In addition, the maps in Figure 34 reveal that the tree heights vary from approx. 10 to 27 meters in a radius of 500 meters around the test location. The tree heights were obtained from an airborne laser scan, which has previously been used in several studies with promising results.

4.1.2.4   Site verification of approach

The two meteorological masts were used to a) determine the input wind conditions applied for testing the different scenarios and b) verify the selected approach. The verification was carried out by comparing the actual and estimated wind speeds using the northern meteorological mast as the simulation location. The results from the verification are presented in the wind profile in Figure 36 below.

Figure 36 Verifying the approach
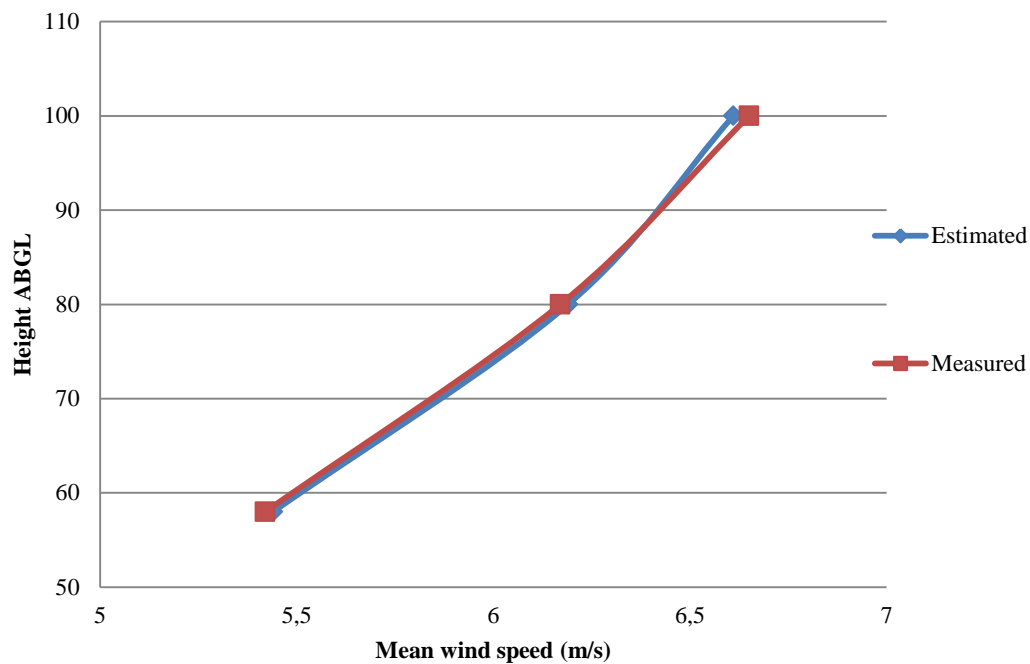
The visual impression of the accuracy of the simulation is supported by a mean difference of 0.026 m/s across all three heights (58, 81, and 100 meters), which means that the selected simulation approach of WAsP and ORA can be verified for this research.

4.1.2.5   Power curve and wind data

The SWT-3.0-113 with a hub height of 115 meters has been selected for this study, as it is an IEC class IIA turbine that matches the wind conditions at the site. The expected power curve from such a wind turbine type is illustrated in Figure 37.

Figure 37 The applied power curve
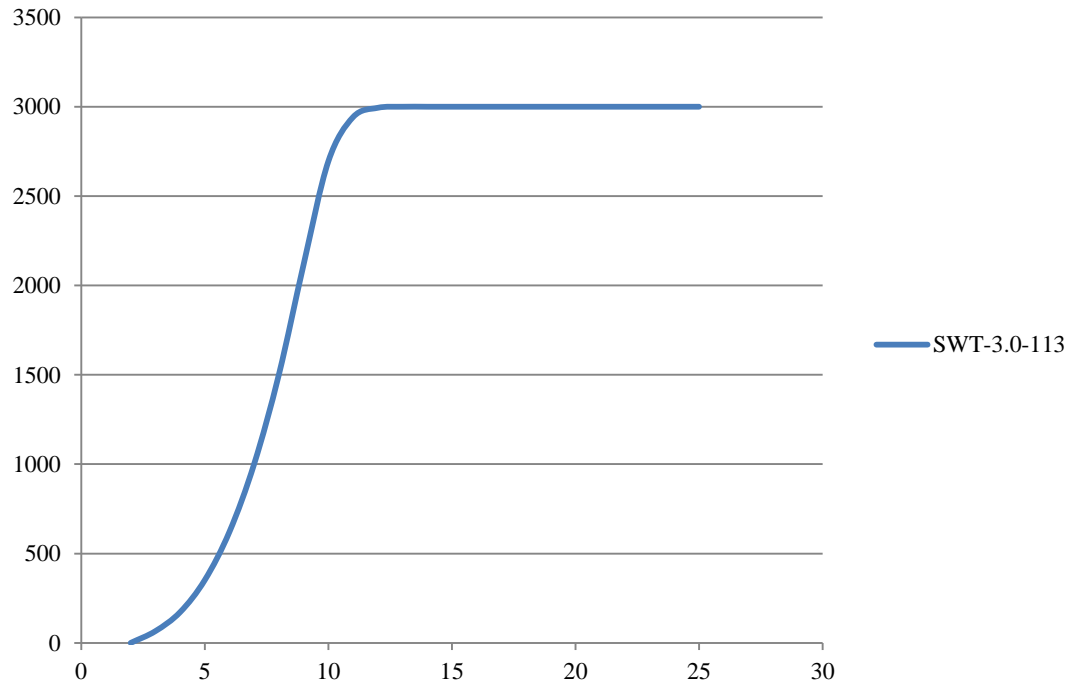
The power curve is suited for the wind conditions, which were measured by the southern meteorological mast. The wind rose and Weibull distribution used for the input wind reference are presented in Figure 38.

Figure 38 The Weibull distribution for the input reference mast
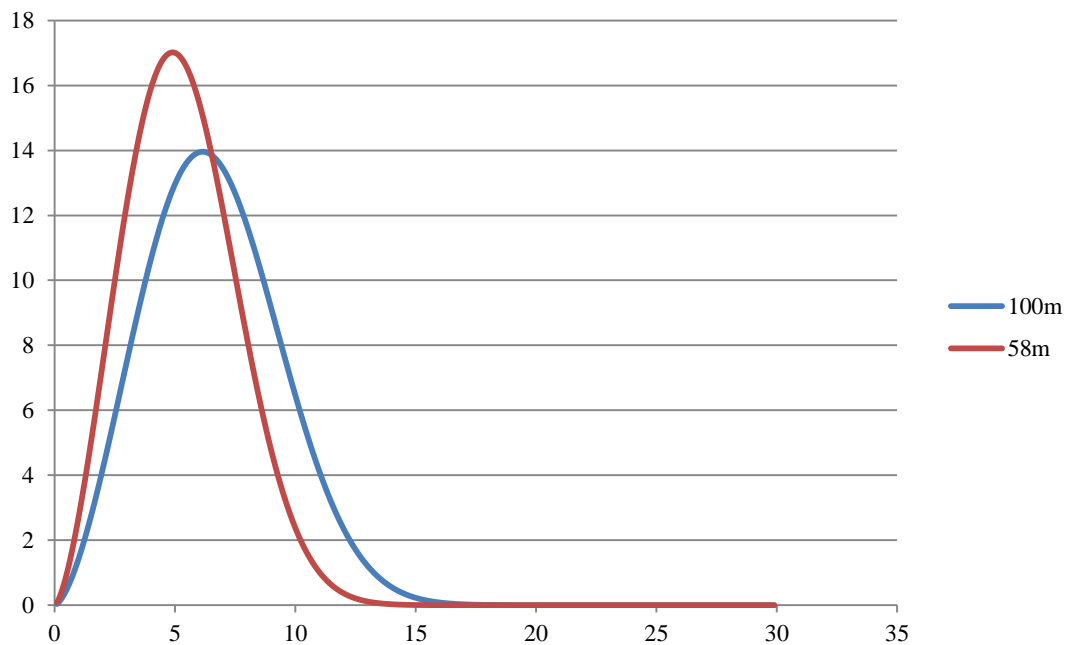
The mean wind speed measured at a two years measurement at 100 meters above ground level is 7.4 m/s, and 6.0 m/s at 58 meters.

4.1.2.6 Interviews

In this study, seven stakeholder groups from the UK, Denmark, and Sweden were interviewed on risks associated with wind power development in forested areas throughout a wind turbine's life cycle. The following stakeholder groups were selected:

- Politicians
- Anti-wind organizations
- The public
- Wind turbine manufacturers
- Wind project developers
- Research institutions
- Forest agencies

The seven stakeholder groups are considered representative for this study's topic. The interviews were carried out as semi-structured interviews and designed to only ask each respondent about the perceived risks in the 1) construction phase, 2) operational phase, and 3) decommission phase of a wind project in a forested area.

4.1.3 Examining the socio-technical framework

The following subsections examine the parameters of the framework in order to discuss whether the expected consequences can be verified.

4.1.3.1 Deforestation's impact on wind resources and annual energy production

The first parameter examined in this research is the consequences of deforestation measured in changes of wind resources and annual energy production, which have been calculated using ORA and WAsP. Given the chosen wind turbine (SWT-3.0-113), the changes in wind conditions have resulted in different annual energy productions, which are presented in Table 27 below.

Table 27 Estimation of wind resources and annual energy production

Scenario	Mean wind speed at 115 m ABGL (m/s)	Annual energy production (MWh/year)
1 hectare	6.68	9,550
4.84 hectares	6.73	9,690
12.92 hectares	6.76	9,794
23.04 hectares	6.8	9,914

The findings in Table 27 indicate that a larger clearing equals a higher energy production, a result of the increased wind speed at hub height. The changes in wind speed have been plotted in the graph in Figure 39 in order to illustrate the wind profiles for each of the four scenarios.

Figure 39 Estimated wind profiles from the four scenarios
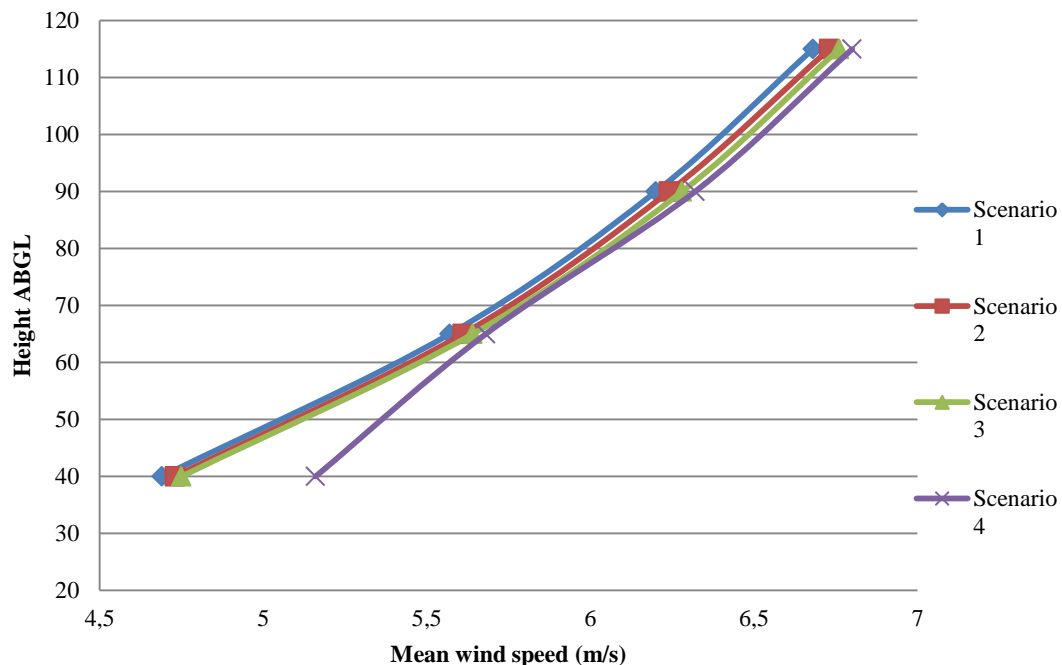
The wind profiles presented in the graph clearly indicate that the larger the clearing, the higher the wind speed. However, most interesting is the difference at the lower heights above ground level, where a significant change occurs between Scenario 3 (12.92 hectares) and Scenario 4 (23.04 hectares), which suggests that the wind flows require a certain amount of changes in the surface for changes to occur in the roughness sublayer.

4.1.3.2 *Social opposition*

While social opposition has been recognized as one of the triggering factors for installing wind farms in forested areas originally (Enevoldsen & Valentine, 2016), it has also come to pose a threat to future wind project development in Northern European forests (Enevoldsen, 2016). The targeted countries of this research have been studied intensively for reasons of social acceptance or opposition (Möller, 2006; Pettersson et al., 2010; Ek, 2005), often with a focus on the impact on humans, such as noise emissions and flicker effects, and on how local ownership and local policies may impact the level of opposition (Ek et al., 2013; Warren & McFadyen, 2010; Enevoldsen & Sovacool, 2016). Despite the extensive amount of literature, only a small number of studies, if any, have adequately studied the specific impact on social opposition when deploying wind turbines in forested areas. However, forestry's impact on natural resources has been a subtopic in a few of the studies. The opposition has primarily been described as locals and owners of hunting huts, vacation houses, etc. who oppose the impact on the animals and birds living in the forest. Additionally, a few studies have described the impact on the forest fauna, as newly planted forests require up to 200 years restoring such fauna.

4.1.3.2.1   The social consequences of deforestation

Naturally, there are diverging views with respect to this parameter. The forest agencies state that wind turbines located in industrial forests are expected to increase the profits for the land owner and the local community, as the forest industry is generating double earnings in terms of the timber, which was supposed to be felled anyhow, and the wind turbine land lease. This view is shared by most stakeholders interviewed, since wind turbines in industrial forests are not the reason for deforestation. However, some locals and national and international anti-wind organizations are still claiming that a) nearby hunting huts and vacation houses are affected by the noise and flicker from the turbines and b) the animal and especially the bird life is impacted by the wind turbines, seeing that industrial forests are often located near natural forests. In addition, a generic reason for opposing wind turbines before they are constructed is the expectation that the forest will result in taller wind turbines that can be seen from further away and will more severely impact the bird life. Nonetheless, this concern has nothing to do with the area of deforestation, but is aimed at wind turbines in forests in general. None of the stakeholders from the wind industry mention social opposition as a considerable risk for wind projects in forested areas in Northern Europe, which could indicate that such opposition is less widespread and that the majority of wind farms are projected to be located in areas with plantations and industrial forests. However, a number of researchers expect more wind farms in forested areas to increase social opposition, as opposed to wind farms being located in the same area, as opposition drops when increasing the installed capacity in a certain area (Ek et al., 2013; Enevoldsen & Sovacool, 2016).

It can therefore be concluded that opposition as a result of deforestation is rarely due to NIMBYism, as the projects deployed in forests are often developed in rural areas and the locals benefit from the timber industry. However, the impact on flora and fauna is a factor that triggers social opposition insofar as natural forests are concerned. Table 28 is based on the statements from the forest agencies, the anti-wind organizations, and the public.

Table 28 Deforestation's impact on social opposition

	Industrial forests	Natural forests
Reasons for social opposition	Impact on the bird life	Impact on the bird life
		Impact on the animal life
		Impact on the flora and Fauna
General opposition	Anti-wind organizations	Anti-wind organizations
		The public
	Few public stakeholders	Policy makers
		Forest agencies

Table 28 provides an overview of reasons for social opposition, including who opposes depending on the type of Northern European forest; industrial or natural. Furthermore, each stakeholder was introduced to the four scenarios and asked which would result in the greatest increase in social opposition. As expected, all stakeholders suggested that increased deforestation would result in increased opposition.

4.1.3.3 *Environmental impact*

In continuation of the reasons discovered for social opposition, the environmental consequences of deforestation also include the impact on bird (Leung & Yang, 2012; Wang et al., 2015) and animal life conditions (Chiras, et al., 2009). Wang et al. (2015) expressed a special concern about the impact on the avian mortality in the top ridges of the forest. This study does not measure or observe the changes in wildlife quantitates and avian mortality after deforestation, though it can be assumed that deforestation leads to a decline in the local wildlife population.

Instead, the impact of deforestation has been converted into comparable CO_2 losses, which has become a topic of increased focus (House et al., 2002; Lawrence & Vandecar, 2015). Only few studies juxtapose wind power with the impacts of deforestation, however. To explore this relationship, this research applies an approach developed by Perks, et al. (2010), implying that the annual emission savings (S_{CO2}) have been calculated using (16) for each of the four scenarios.

(16) $$S_{CO_2} = 8760 \times \frac{p_{cap}}{100} \times n_{WTG} \times c_{WTG} x E_{CO_2}$$

Where p_{cap} describes the capacity factor (%), n_{WTG} is the number of wind turbines, c_{WTG} is the installed wind turbine capacity (MW), and E_{CO_2} is the emission factor ($CO_2 \, MWh^{-1}$). The output from (16) has been applied for each scenario and subtracted from the CO_2 loss of the deforested forest on the assumption that a wind turbine saves 430gCO$_2$/kWh by replacing fossil fuels (DEFRA, 2008). The CO_2 loss has been estimated using the carbon calculator tool provided by the Scottish Government (2016). Additional parameters such as usage of timber for biomass or losses due to road construction, draining, and potential need for backup power Perks, et al. (2010) have not been included in this research.

In Table 29 below, the environmental impact of each scenario has been estimated using an average tree height of 12 meters for dense forests covered 50% by Norwegian spruce and 50% by Scots pine in a cold climate. This equals a storage of 280 t/CO_2 per hectare.

Table 29 Environmental consequences of deforestation (measured in CO2)

Scenario	CO₂ savings after 1 year of operation	CO₂ savings after 20 years of operation	Break-even (years)
1 hectare	1,624	79,647	0.6
4.84 hectares	-7,850	71,317	2.9
12.92 hectares	-27,866	52,151	7.6
23.04 hectares	-52,940	28,058	13.4

The calculations indicate that increased deforestation results in reduced environmental profit, as the potential gains are too small compared to the additional CO_2 loss caused by the clear-felling. It has been assumed that the felled trees have not served any purpose, which otherwise would have altered the results.

4.1.3.4 Levelized cost of energy

Wind power can be compared to other energy sources and is even within different wind configurations when applying the levelized cost of energy as the dominant comparative factor. In (17), the function applied for the four different scenarios of deforestation is applied by including the potential cost and income from deforestation.

(17)
$$LCOE_x = \frac{C_{WTG} \times CRF_{WTG} + C_{OM} + Tree_{Cost} - Tree_{Income}}{AEP}$$

The levelized cost of energy (*LCOE*) for different scenarios, *x*, is determined by C_{WTG}, which is the cost of the wind turbine(s), CRF_{WTG}, which defines the capital recovery factor for the wind turbine(s), and C_{OM}, which is the annual cost of operation and maintenance. The cost of deforesting is determined by $Tree_{Cost}$, and $Tree_{Income}$ is the potential income from timber. The capital expenditures (CAPEX) for the wind turbine are defined in Table 30 below.

Table 30 CAPEX for the selected wind turbine

Parameter (onshore)	Percentage of CAPEX (%)	Cost ($)
Wind turbine	70	5,355,000
Civil work and electrical infrastructure	21	1,606,500
Planning	9	688,500
All (total)	100	7,650,000

The estimated costs are based on a calculation performed by IRENA (2015), which has been applied for this type of wind turbine. The numbers are based on the fact that the cost of the wind turbine itself weighs 70% of the combined capital expenditures and the fact that the average capital cost of onshore wind turbines was found to be 1,785 (USD/kW) (IRENA, 2016). The operational expenditures are based on the mean cost per produced kWh for onshore wind turbines in Europe, which is 0.019 (USD/kWh) (IRENA, 2016), for which reason the operational expenditures (OPEX) are indicated for each of the four scenarios.

Table 31 OPEX for the selected wind turbine type

Scenario	OPEX costs ($)
1	181,450
2	184,110
3	186,086
4	188,366

In addition to the capital and operational expenditures, the capital recovery factor is estimated in order to determine the levelized cost of energy from the estimated lifetime of 20 years.

(18)
$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1}$$

The capital recovery factor (CRF) is determined by I, the discount rate, and n, the system life time. When assuming a discount rate of 3% (Gifford, et al., 2011) and an estimated lifetime of 20 years, the capital recovery factory is 0.067 following (18).

The potential income of timber and expected cost of deforestation are based on an interview with the Swedish Forest Agency, with $ 31,631 for one hectare of timber based on Norwegian spruce and Scots pine and assuming a high density forest with 60% saw logs, 40% pulpwood, and 600 m^3fpb/hectare.[4] The costs using the same specifications would be $ 6,659 for the deforestation of one hectare of Norwegian spruce and Scots pine.[5]

4.1.3.5 *The impact of deforestation on the levelized cost of energy*

Following (17), the levelized cost of energy for each of the four scenarios has been calculated.

$$LCOE_1 = \frac{\$7650000 \times 0.067 + \$181450 + \$6,659 - \$31,631}{9550 \ MWh} = \$70.1/MWh$$

$$LCOE_2 = \frac{\$7650000 \times 0.067 + \$184110 + \$32230 - \$153094}{9690 \ MWh} = \$59.4/MWh$$

$$LCOE_3 = \frac{\$7650000 \times 0.067 + \$186086 + \$86034 - \$408673}{9794 \ MWh} = \$38.4/MWh$$

$$LCOE_4 = \frac{\$7650000 \times 0.067 + \$188366 + \$153423 - \$728778}{9914 \ MWh} = \$12.7/MWh$$

The potential timber income clearly indicates that scenario 4 results in the lowest LCOE. However, the wind farm owner may not necessarily be the forest owner, for which reason two other possible outcomes have been applied on the four scenarios and presented in Table 32 below.

Table 32 Consequences of excluding incomes and costs from deforestation

Scenario	Excluding all income from deforestation ($/MWh)	Excluding both income from and cost of deforestation ($/MWh)
1	73.4	72.7
2	75.2	71.9
3	80.1	71.3
4	86.2	70.7

When comparing the scenarios without considering the potential timber income, the first scenario is the most profitable. However, when excluding both income and cost, the fourth scenario provides a

---

[4] fpb = stem volume, including bark and excluding top canopy.
[5] The currency was converted from SEK to USD using www.valutakurser.dk on April 20, 2017.

lower LCOE due to the increased annual energy production. The estimated LCOE for each of the four scenarios has been compared to different suggestions for LCOE for onshore wind power in the diagram in Figure 40 below (EIA, 2016; IRENA, 2016; Lazard, 2015; Lazard, 2016; Open Energy Information, 2015).

Figure 40 Comparing the LCOE of the four scenarios with different suggestions
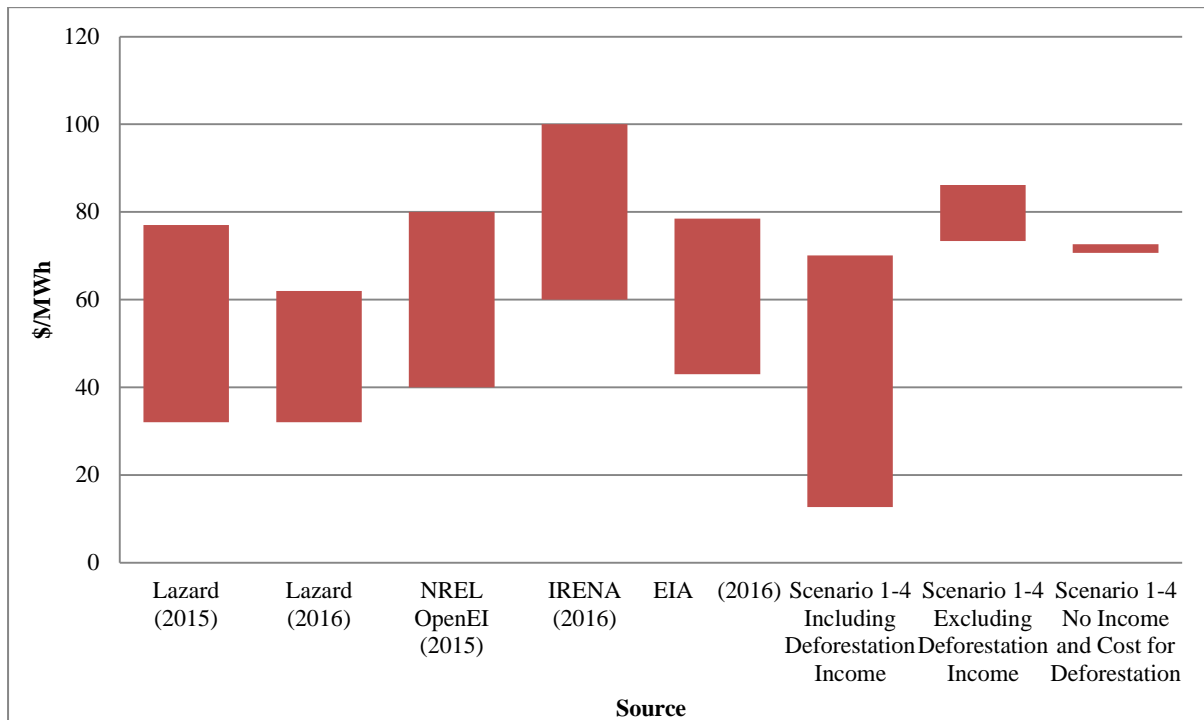
When examining Figure 40, it becomes clear that including deforestation income clearly optimizes the business case, whereas exclusion of timber as an income equals a higher LCOE.

4.1.4 Conclusion

The final verified version of the socio-technical framework is introduced in Table 33 below. A few changes have been made to the beta version of the framework.

Table 33 The socio-technical consequences of deforestation when siting wind turbines in Northern Europe

Parameter	Expected consequences of deforestation
Wind resources	Deforestation only has a minor impact on the performance of the wind turbine, and for wind speeds in the roughness sublayer, the clearing size around a wind turbine does not have a mentionable impact before exceeding at least 13 hectares.
Social opposition	Deforestation does increase the likelihood of

	experiencing social opposition. However, when developing wind farms in plantations instead of natural forests, the social opposition is less likely to occur and the groups of opponents are fewer in number.
Environmental impact	It is possible to achieve CO_2 savings in spite of the deforestation due to the increased annual energy production from a renewable source. However, more deforestation does not result in enough additional energy to defend deforestation of a larger area.
Levelized cost of energy	If it is possible to sell the timber from the deforestation, the increased annual energy production and income from timber will result in a lower levelized cost of energy after deforestation. However, without income from timber, the deforestation should be kept at a minimum.

The findings of this study were based on a single case study in Sweden, why future studies might produce different results for other regions. However, several interesting results came to light.

The resource assessment did reveal an increase in annual energy production when clear-felling a larger area of trees, but the increase in the annual energy production was only 3.8% when comparing a clear-felling of 1 hectare to one of 23.04 hectares. Another interesting aspect was the increase in wind speeds around 40 meters above ground level or approx. three times the tree height, which was obtained when clear-felling 23.04 hectares around the turbine. This could also potentially indicate a decrease in turbulence intensity, implying that the deforestation may have other benefits that have not been examined in this study. In conclusion, as to the first parameter of the socio-technical framework, deforestation will increase the annual energy production; this only slightly, however, suggesting that additional studies on the loads experienced by the wind turbines should be initiated.

The interviews and previous studies found that deforestation does have an impact on the level of social opposition. However, the opposition seems to be more severe when deploying wind turbines in natural forests. It is thus advisable to develop wind projects in plantations and industrial forests, as stakeholders perceive the forest as part of an industry, which wind power has the potential to benefit financially.

One of the reasons for social opposition is naturally the environmental consequences of deforestation. This research therefore examined a worst case scenario, as it was assumed that all the trees felled were decommissioned without any purpose. It was discovered that the CO_2 loss of one hectare of deforestation in a typical Swedish forest would be repaid in approx. seven months, whereas an area of 23.04 hectares would require more than 13 years of energy production from the wind turbine type applied at the case location. It can therefore be concluded that there is no incentive to increase the

deforestation in order to increase CO_2 savings. The third parameter in the socio-technical framework can be further adjusted by taking several scenarios of deforested trees into consideration, e.g. usage for bio pallets, timber, etc. Furthermore, it is important to stress that a range of other greenhouse gasses can be considered, just as strategies for replanting trees would change the outcome.

The fourth and final consequence of deforestation for new wind project development is the impact on the levelized cost of energy. Several scenarios were examined in this connection. It was discovered that the income for a wind project can be increased significantly, if the wind project developer is able to take ownership of the forest, as the deforestation of 23.04 hectares Norwegian spruce and Scots pine would equal an LCOE of $ 12.7 per MWh compared to $ 70.1 per MWh for the deforestation of 1 hectare. This is due to the potential income from timber in Sweden. However, when excluding the potential income from timber, the additional energy production is not sufficient to cover the cost of felling the trees, as the LCOE for the fourth scenario with deforestation of 23.04 hectares Norwegian spruce and Scots pine would equal an LCOE of $ 86.2 per MWh compared to $ 73.4 per MWh for the deforestation of 1 hectare. When comparing the LCOE of the case study to guidelines presented by market reports, it can be concluded that the additional cost of deforestation makes wind projects in forested areas more expensive per unit electricity produced compared to other onshore projects.

The socio-technical consequences introduced in this research study are meant to inspire stakeholders in the wind industry and the forest industry to look into strategies for optimizing the future expansion of wind projects in forested areas. Moreover, the framework is expected to inspire academia to conduct further studies and develop a project model that secures a smooth development process of wind projects in forested areas in Northern Europe and potentially the entire world.

4.2 Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden

Installation of onshore wind farms has increased in the past decade all over Sweden, and as a result, more wind projects are facing challenges, such as social opposition and lack of space, which potentially complicate resource assessments. As a response to the current challenges in the Swedish wind industry, this study examines and develops a strategic map of potential areas for the construction of new farms in Sweden. The analyses for making the map are performed using a holistic research strategy that focuses on everything from social to technical challenges. The map is based on an extensive data collection consisting of a comprehensive wind dataset mixed with the outcome of large-scale qualitative studies that include five dominating stakeholder groups in the Swedish wind industry and detailed information on restrictive areas. Consequently, this research presents a resource map, which aims at inspiring all stakeholders in the Swedish wind industry to further develop the successful case of wind power in Sweden. Furthermore, the current research aims to update ongoing debates in the wind energy literature, and finally, it introduces a tool that can be used in all phases of a large-scale energy strategy, where wind power is involved.

4.2.1 Introduction

Wind power has become the most important technology in the renewable energy transition, which can be confirmed every year by the increasing number of wind turbines, employees in the wind industry, new countries interacting, the role of supporting politics, and most importantly, the installed energy capacity. The development in Sweden is no different than the one observed globally, and as revealed in the graphs in Figure 41, the annual development of installed wind power capacity in Sweden was actually more explosive than the global development from 2007-2015.

Figure 41 The annual development of installed wind capacity in Sweden vs. the world.
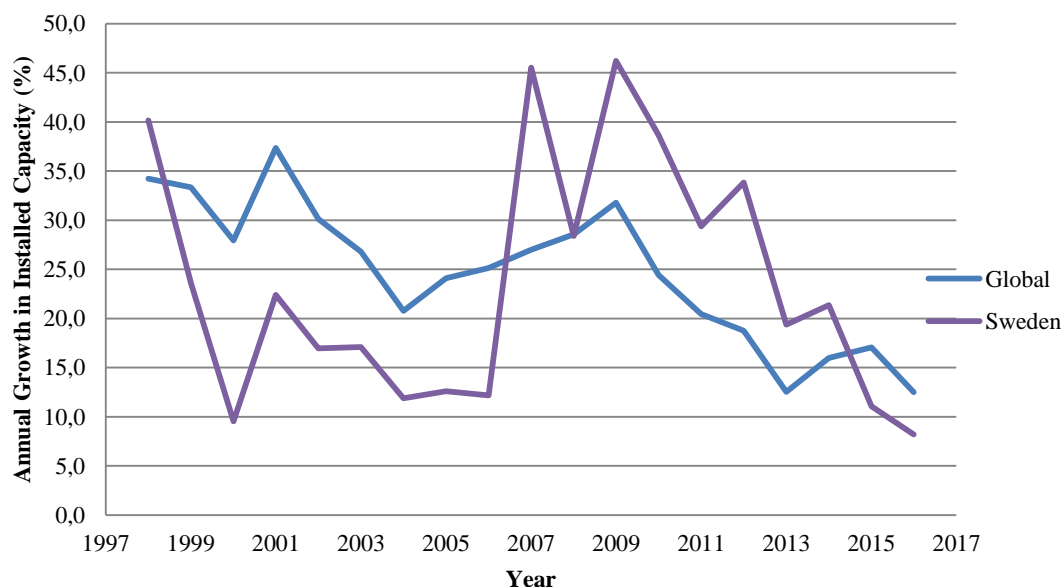
The positive development of installed wind capacity in Sweden in the past decade was ensured by establishing and renewing the green certificate schemes in 2003 and 2006, respectively (Bergek, 2010). This additional financial benefit to the market price for green electricity invited the large wind project developers and investors to focus on the Swedish market (Darmani, 2015; Gullberg & Bang, 2015), and as a result, the Swedish installed capacity (MW) has risen from 509 MW at the end of 2005 to 6519 MW at the of 2016 (The Wind Power Net, 2016). The national energy policy has in many cases been the most important parameter for the promotion of wind power (Meyer, 2007), and when compared to its Danish neighbors, Sweden entered the wind market much later, mainly due to an energy policy not focusing on wind as a solution to the oil crisis in the 1970s (Carlman, 1988). The result of the late entrance is one of the main reasons why the majority of Swedish wind power is based on multi-megawatt wind turbines. These types of wind turbines are more expensive than the ones introduced in the pioneer stage in Denmark, making it harder to attract local investments, which is a key factor influencing social acceptance (Enevoldsen & Sovacool, 2016). This produces an unfortunate mix in combination with a decentralized political system (Pettersson, 2008), allowing the Swedish municipalities and local inhabitants to decline wind projects – an outcome that has been targeted and determined by previous studies (Pettersson, et al., 2010; Ek & Persson, 2014). The recent decline in annual growth presented in Figure 41 furthermore raises concerns on the future development of wind power in Sweden.

4.2.1.1   *Addressing the Risks*

The increasing social opposition can be seen as a direct response to Sweden's energy policy during almost five decades. In 2014, Ek & Persson (Ek & Persson, 2014) analyzed the results of a large study, which involved the opinions of 1,500 respondents and a sample from a web panel of 90,000 Swedes. The results revealed a majority of support for wind power. Yet people prefer offshore wind power, and studies have shown that Swedes are even willing to pay a higher price for electricity, if the wind turbines are deployed away from recreational areas, and without harming avian and local animal life (Ek & Matti, 2015). Just as interesting, the quantitative study revealed that the Swedes want to have the opportunity to invest in new wind farms and to be involved in the planning process (Ek & Persson, 2014), both reasons that, if lacking, are in alignment with synthetic reasons for social opposition (Enevoldsen & Sovacool, 2016). Swedish studies have furthermore investigated the local benefits of installing wind power in rural areas of Sweden, which can be seen as a reaction to the challenges (Ejdemo & Söderholm, 2015) that wind project developers are facing in those parts of Sweden. Being aware of the complications of social opposition resulting from the late introduction of wind power as well as an energy policy favoring large-scale investments while having a decentralized political system for the approval of prospective wind farms, Sweden could be seen as a risky place for investors. In addition, a study examining wind turbine risks in Northern Europe summarized one of the greatest risks of wind project delays in Sweden as being the public inquires and opposition towards landscape interference (Enevoldsen, 2016).

However, another study revealed that the opposition experienced in Sweden is very similar to one that hydropower, nuclear, and biomass energy encountered when introduced as an energy source in Sweden (Anshelm & Simon, 2016). In fact, a number of the wind power opponents have become a synonymous with supporters of nuclear and hydropower, hence the belief of sources that are more environmentally friendly and effective (Anshelm & Simon, 2016). In a study of French energy policy, the same pattern of opposition has previously been found as an explanation of the challenges

of developing wind projects in France (Szarka, 2007), why such ideology poses a threat to the continued development of wind power.

The efficiency of onshore Swedish wind projects relies largely on the site and resource assessment, as the majority of Sweden (66%) is covered by forest (Swedish Forest Agency, 2014), and researchers have found that forests represent a challenge to predict wind conditions (Enevoldsen, 2016). This is particularly the case in Sweden, where industrial forest causes deforestation in structured patterns, which changes the formation of the forest into heterogeneous clusters leading to continuous changes in the wind conditions above the forest canopy (Enevoldsen, 2016). In combination with the socio-political demands of avoiding wind turbine deployment in recreational areas as well as the motivation of interacting with the Swedish people in the planning process, a high resolution wind resource map or atlas consisting of factors representing the technical challenges and revealing areas with favorable wind conditions will be constructed and discussed in this research. A socio-technical wind atlas will not only reveal where to avoid challenges for wind farm deployment, but also support the promotion of wind power in Sweden, which is indeed needed, as the Swedish government has an ambitious target of 30 TWh/year to be generated by wind power in Sweden by 2020 (Anshelm & Simon, 2016).

4.2.2 Research Material and Methods

This section introduces the methods and materials used to collect and analyze data for constructing the socio-technical wind atlas for future promotion of wind energy in Sweden. The introduction and structure of the data collection in this research is based on a literature search conducted using the search words "Wind Energy", "Wind Power", and "Wind Turbines", which have been combined with "Sweden" and "Onshore", "Wind Atlas", and "Resource Assessment" using the databases from Google Scholar and www.sciencedirect.com. The total number of papers was enormous, for which reason literature was analyzed until a research design for creating the socio-technical wind atlas was established. This resulted in a total amount of 20 papers. As presented in the introduction of the research, the literature review revealed some of the challenges for Sweden's desired wind power expansion, which a socio-technical wind atlas will help to limit.

4.2.2.1 Wind Data

The extensive dataset for constructing the wind resource map has been collected through interactions with wind turbine manufacturers and the creators of an existing wind atlas for Sweden. The wind data collected for this research is based on the wind speed measured on more than 430 onshore wind turbines and more than 25 meteorological masts located all over Sweden. The physical measurements have been coupled with a mesoscale high-resolution dataset (500 m x 500 m) from WeatherTech and implemented in the map following the Voronoi method. The position of the physical measurements has been anonymized, yet Figure 42 gives a rough introduction to the location of the different measurement devices.

Figure 42 Physical measurement devices.
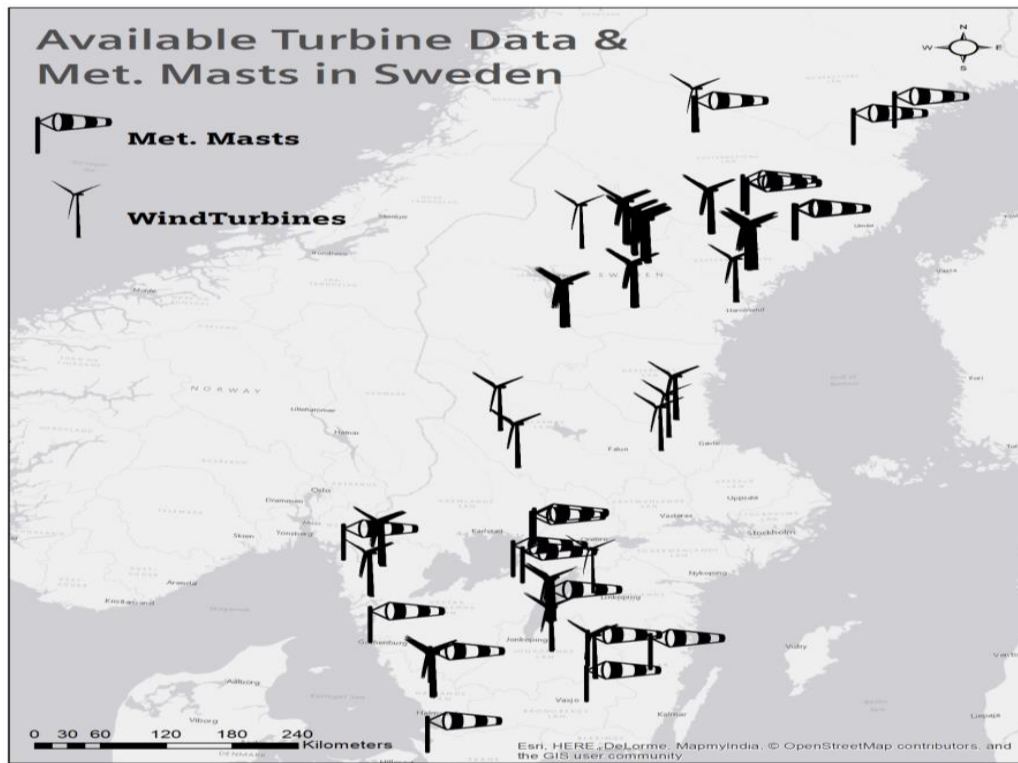
As illustrated in Figure 42, the extensive amount of physical measurement devices cover the majority of Sweden, as the gap between Sweden and Norway is dominated by mountains and therefore not appropriate for deployment of wind turbines. Furthermore, despite being a rather novel wind country, Sweden is already covered by different sources of mesoscale dataset for wind conditions; few, however, with data at the hub height of a modern multi-megawatt wind turbine (approx. 100 m), which is required for siting wind turbines in forested areas. One dataset with estimated wind speeds for such height is the high-resolution mesoscale dataset from WeatherTech. The mesoscale dataset was constructed using the MIUU method developed at Uppsala University in Sweden. A statistical analysis revealed a minor error (a delta difference of 7%) in the wind speeds predicted at 100 m above ground level when compared to the measurements from ten meteorological masts, why the dataset from WeatherTech is considered highly reliable for the detection of wind resources in Sweden.

The test of the combined wind atlas is presented in Table 34 below; however, the position of the reference meteorological masts has been anonymized.

Table 34 Testing the wind atlas.

Wind atlas (100 m)	Measurement height ABGL (m)	Measured wind speed (m/s)	Delta difference (%)	Delta difference (m/s)
7.17	100	7.36	2.6	0.19
6.64	100	7.01	5.3	0.37
6.75	100	7.02	3.8	0.27
6.96	100	7	0.6	0.04
7.63	100	8.1	5.8	0.47
7.10	100	6.3	12.7	0.80
6.72	94	6.31	6.5	0.41
6.82	99	6.29	8.4	0.53
6.90	98	6.7	3.0	0.20

Nevertheless, Figure 42 reveals that the physical measurement locations cover the majority of Sweden. Thus, adding these measurements is considered an improvement of the existing wind atlas from WeatherTech. From Table 34, such considerations have been validated and revealed by the absolute mean delta difference of 5.4% between the measurement masts and the combined wind atlas.

4.2.2.2 Qualitative Studies

The introduction of this research revealed that previous studies already have collected and analyzed quantitative data on the Swedes' perception of future wind farm locations. It has therefore not been necessary to conduct new data collection and make new interpretations, since the novelty and quality of the existing studies easily can be transferred to this research. Nevertheless, one criticism of using the existing studies in this context seems to be the lack of investigating all stakeholders in the Swedish wind industry as well as the stakeholders' perception of developing onshore Swedish wind power. In order to target a broad and representative group of stakeholders, a model following three steps for assessing stakeholders has been used (Enevoldsen, et al., 2014): (1) Revealing stakeholder groups, (2) screening the stakeholder group members, and (3) analyzing the stakeholders to identify respondents. The stakeholders have been anonymized, but a brief description of each stakeholder group is presented in Table 35 below. The interviews have been analyzed for each organization in the different groups, and as output, the synthetic considerations of risks for future development of onshore wind power in Sweden are listed.

Table 35 The perceived risks for new wind project development in Sweden.

Stakeholder groups	Organization	Greatest risks for new wind project development in Sweden	Other comments
Policy	Research institutions	Swedish municipal planning monopoly allows anti-wind organizations to impact the decision of prospected wind farms. Due to a lack of vertical integration, Sweden, therefore, has a longer development time than the other Nordic countries.	Opposition is rare due to NIMBY reasons in Sweden. The northern part of Sweden, which is more rural than the southern, is facing strong opposition due to the impact on the landscape.
Policy	The Swedish Forest Agency	Forestry is a very important part of the Swedish economy, and it is believed that forestry and wind energy can be mixed to make a greater profit from each forest.	Wind power can add value to industrial forests.
Policy/Public	Anti-wind organizations	Protests against wind projects, as there is a lack of involvement from the people in the municipality of the wind project. Furthermore, wind power as an energy source is rated to have a lower efficiency than hydropower and nuclear energy.	Wind turbines will destroy the nature during transportation, construction, operation, and dismantling.
Wind assessment	Research institutions	While the wind resource is often overestimated in forested areas, the loads on the wind turbines, on the other hand, are underestimated, which overall leads to less efficient wind turbines.	The meteorological masts are often located with little impact from the forest to represent the best possible business case. This is a risk in heterogeneous forests.
Wind assessment	Wind project developer	It takes substantial resources to assess, if a forested area is in fact suitable for a wind project, as studies on animal life need to be conducted. In addition, it is necessary to identify whether the area is protected.	It complicates and increases the development costs, if there is social opposition towards the wind project.
Public	Swedish citizens	The height of wind turbines has made it possible to install them anywhere, and thus, they can be deployed in locations, where people are not disturbed by their presence.	The public wants to influence the location of the wind turbines and have local benefits from such projects.
Wind assessment	Wind turbine manufacturer	Sweden is known for its trees and forest industry, which means that there is plenty of data supporting the growth and felling of trees. Without trees, it would be difficult to predict the wind conditions and operational performance of the wind turbines.	The distance to the main grid can be very long in Sweden.

The risks revealed in the qualitative studies and presented in Table 35 verify the findings from the literature review presented in section 1.1 of this research paper. It furthermore becomes clear that the wind industry in Sweden is in need of a resource map which takes into consideration the need of all stakeholder groups, as they clearly all have a role to play in the future of the Swedish wind industry.

The opinions from the stakeholder groups have been implemented in the social constraints in the final socio-technical wind atlas.

4.2.2.3   Constructing a Socio-Technical Wind Atlas using GIS

The results of the literature review revealed a range of academic contributions on wind atlases for different regions of the world, which will be used to structure the framework for the Swedish wind atlas.

The majority of the existing wind atlases only focus on the wind conditions and the construction of large resource maps by using different computational approaches (Mortensen, et al., 2006; González-Longatt, et al., 2014; Nawri, et al., 2014). Studying previous atlases confirms that the high resolution of the mesoscale dataset used in this research combined with the extensive amount of physical measurement devices creates a strong data foundation compared with the previous studies. More applicable to this study are previous examples of GIS-based wind atlases, which include more parameters than the wind conditions. Such atlases have been developed all over the world (Sliz-Szkliniarz & Vogt, 2011; Noorollahi, et al., 2016) and provide an extra dimension to the existing resource maps. An ambitious study also examined the proper locations for wind turbines in Sweden using GIS-software by combining mesoscale wind data with environmental considerations. This study, however, did not use an extensive amount of detailed wind data from physical measurement devices, neither did it investigate social opposition and the potential threat of such or the perceptions of the major stakeholders in the Swedish wind industry. The work of Noorollahi et al. (2016) furthermore classified areas for wind farm suitability by weighting the amount of protected areas against the wind conditions. It has therefore been decided to follow some of the same principles for this research, for which reason some restrictions for wind turbine development have been taken into account. The restrictions and the actions performed are presented in Table 36 below.

**Table 36 Restrictions and actions applied for the socio-technical wind atlas.**

Restriction	Action	Why
Roads and waterways	A buffer radius of 200 meters has been applied for further restrictions.	A certain distance needs to be applied to roads in case a wind turbine should break and/or fall. Adding roads to the atlas also serves as an important feature in the planning process, as the infrastructure is important in the construction phase.
Railways	A buffer radius of 200 meters has been applied for further restrictions.	A certain distance needs to be applied to railways in case a wind turbine should break and/or fall. Adding railways to the atlas also serves as an important feature in the planning process, as the infrastructure is important in the construction phase.
Buildings (residential, industrial, and public)	A buffer radius of 200 meters has been applied for further restrictions.	Distances to buildings in Sweden are determined by the noise and flicker emissions from wind turbines, which vary from each wind project. Therefore, a radius of 200 meters has been applied as a minimum distance, though it might be more or less for a given site.
Protected buildings (castles, monuments, etc.)	A buffer radius of 200 meters has been applied for further restrictions.	A distance of 200 meters has been applied to protected buildings, as the decentralized Swedish political system allows members of municipalities to complain about new wind projects, where protected buildings have often been the source of such complaints in international public inquiries (Warren & McFadyen, 2010).
Protected areas (Natura 2000)	No buffer radius has been applied, only	According to the stakeholder analysis, it was important to avoid wind turbines in scenic areas, which are often restricted from any

	the area itself.	building projects. Sweden has several areas that are protected due to various reasons, such as rare bird species, large population of wildlife, certain tree types, etc.
Lakes	No buffer radius has been applied, only the area itself.	Despite the fact that not all Swedish lakes are protected areas, this part has been considered a restriction due to the fact that installation of wind turbines on lakes would require offshore wind turbines and foundations, which has been found more costly than the onshore counterpart.

We also considered applying restriction areas for existing operating wind turbines, though this is not considered a restriction, as repowering of the existing wind farms will be a future option.

The geodetic agencies have made many of their data publicly available in a common vector data format. The Swedish 'Länsstyrelsen', for example, has hundreds of shape layers available for downloading on their website divided in national and county data (Länsstyrelsen, 2016). The social and environmental constraints found in this database were used to construct the restriction layer. As another data source, the open street map foundation was used to incorporate infrastructural data of Sweden. Shape files of buildings, streets, railways, and waterways as well as other waters such as lakes and reservoirs were acquired from the German geodata portal, 'Geofabrik' (Geofabrik, 2016). The restrictions were applied following the research design summarized in Figure 43, which introduces three steps of the geo-processing methodology.

Figure 43 Research design for the socio-technical wind atlas.
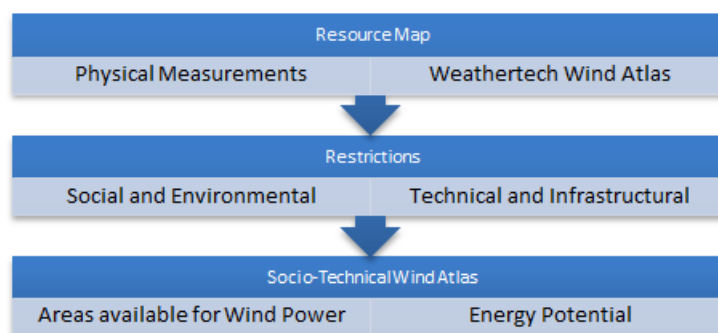
The first step is the merging of the resource map from physical measurements provided by the wind industry and the WeatherTech wind atlas. The second step consists in merging the social and environmental restrictions and the technical limits of buildings, and the third step involves the overlay of these to highlight the areas available for wind energy farming and show their energy potentials. In conducting these steps, different tools were used. In the first step, the wind resource map from WeatherTech had to be merged with the physical measurements. The wind resource map was downloaded in .txt format and imported in QGIS as a shapefile point layer. Since the .txt file derived from a raster file, the output points from this step were arranged in a 500 x 500 m grid. These two shapefiles could be easily merged together with no further intermediate step. However, this would result in an issue, where points show different wind speeds for the same area, but since there is no real overlapping points, it is technically not possible to simply replace the points. To deal with this issue, the affected points from the WeatherTech atlas were intersected by a 500 m buffer around the physical measurements, ensuring that no wind atlas point was closer to a physical measurement point

than the normal grid distance. Subsequently, the resulting point layer was transformed into a raster file to ensure a comprehensive coverage of the whole area of Sweden. These steps were conducted using QGIS. In the second step, a high amount of data had to be managed. The downloading, organizing, and merging of the various layers were performed using ArcGIS. The layers to be merged were downloaded in polygon shapefile format and then organized into social and environmental restrictions as well as technical and infrastructural restrictions. Since most of the layers for the social and environmental restrictions were already in a suitable format, no further actions were needed. Some of the infrastructural restrictions required the intermediate step of calculating buffer zones around the road, railway, and waterway network of Sweden, since they were provided in line shapefile format. These buffer zones show the building restrictions on each side of these infrastructural features, and were determined to be 200 m. The same distance was also applied to buildings and waterways. The resulting layer shows all social and environmental restrictions as well as all technical and infrastructural restrictions. The third and last step was to combine these two layers into one map. The map shows the two layers as an overlay by using the transparency functionality and adding other geographical items, such as legend and scale in the print composer of QGIS.

4.2.3   Results and Discussion

This section presents the results for the Swedish socio-technical wind atlas by analyzing and introducing 1) the wind resource map, 2) the map of restrictions, and lastly, 3) the final socio-technical wind atlas.

4.2.3.1   The Wind Resource Map

A vital part of this research is the wind conditions, and the map in Figure 44 reveals the Swedish wind speeds based on an updated wind atlas consisting of data from the physical measurement devices and the wind atlas from WeatherTech.

Figure 44 The combined wind resource map.

155
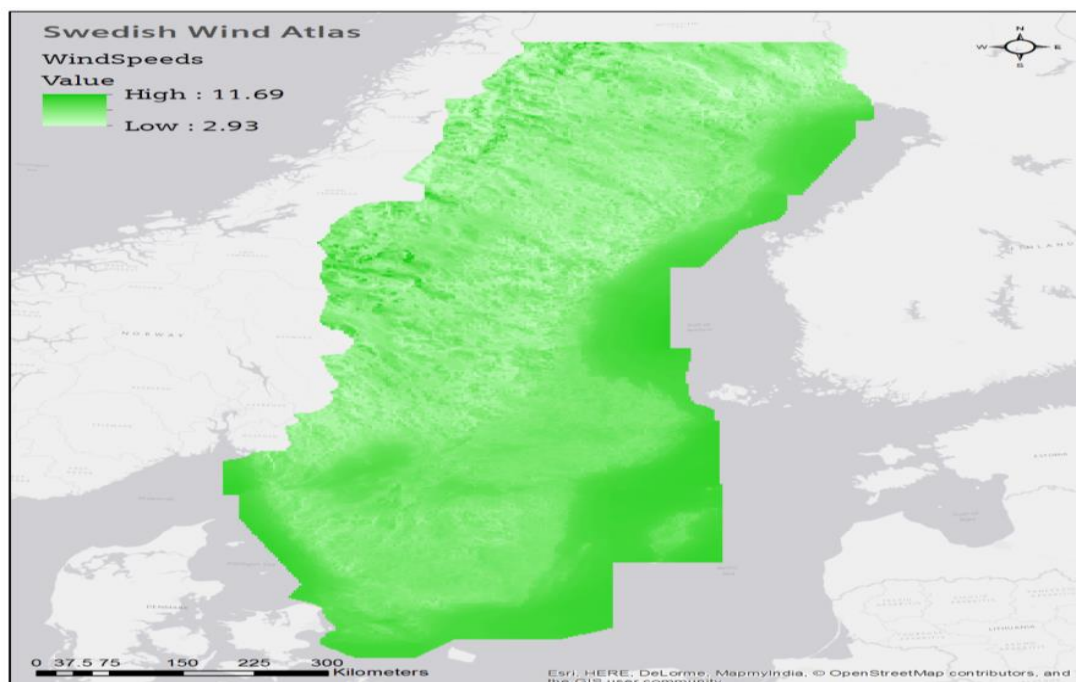
When examining the visual impacts shown on the map, it becomes clear that the areas with the highest wind speeds are along the coasts and in the southern and southeastern part of Sweden, i.e., areas with high population densities. In these areas, cabling and transport cost can be decreased; however, most likely, these areas also have the most restrictions. As visualized on the map, the wind speeds are also high in some parts of the mountains separating Sweden from Norway, but this area has not been found suitable for wind turbines due to expected additional costs for installation and lack of infrastructure.

4.2.3.2   Mapping the Restrictions

The following figures display the restrictions layers added on top of the wind resource map, which were compiled after the merging and buffering. The restrictions presented in Table 36 have been combined into three overall restriction groups: 1) Buildings, 2) national and natural constraints, and 3) infrastructure.

The population of Sweden is 9,822,093 as of January 2016 (Countrymeters, 2016), which equals a population density of 21.8 persons per km^2 over the total 450,295 km^2 area. This is a relatively small population density, and the building restrictions, which also include industrial and public buildings, are therefore not one of the major restrictions to future wind project development. The restrictions based on buildings are illustrated by the pink dots in Figure 45.

Figure 45 Restrictions based on buildings.
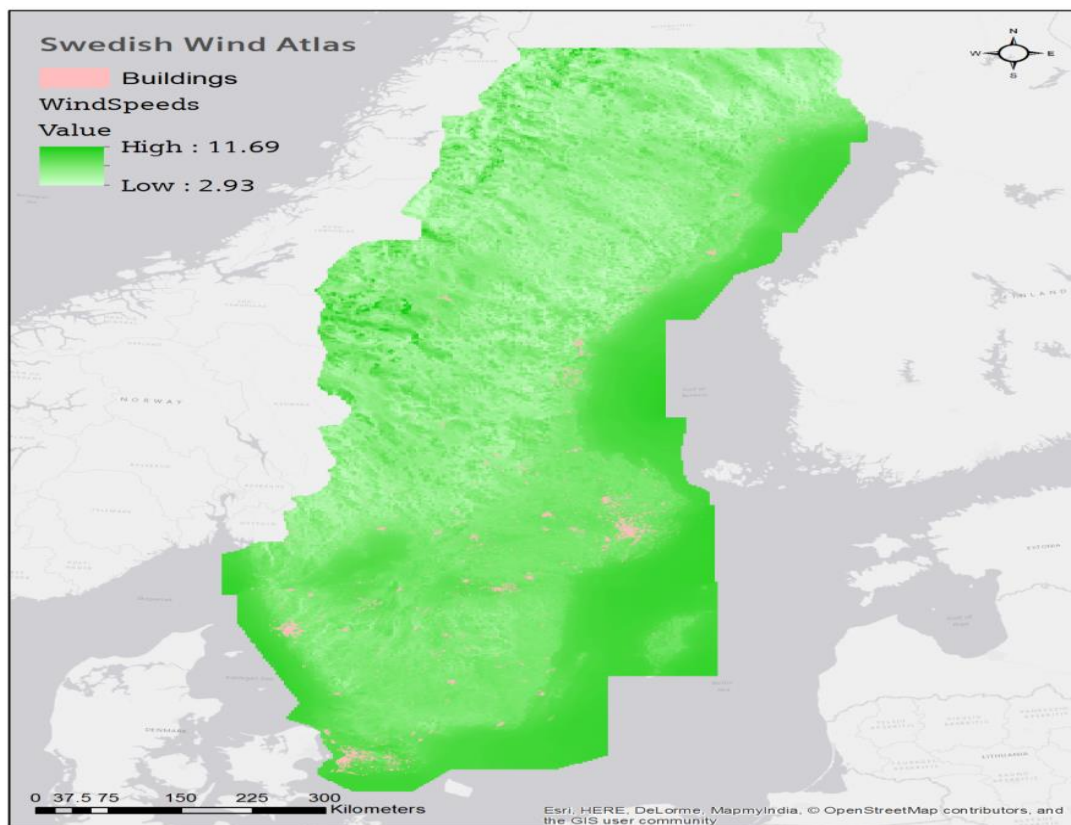
The area covered by buildings, including buffer zones, was calculated as 12,845 km^2. Sweden has several national constraints based on heritage buildings and areas, protected natural areas, and protected wildlife. The restrictions in Figure 46 are more extensive than the buildings shown in Figure 44, where the national and natural constraints are added to the building restrictions. These constraints also cover potential offshore wind project development. However, the offshore area has not been taken into account in this research, but has been kept for informative purposes.

Figure 46 National and natural restrictions.
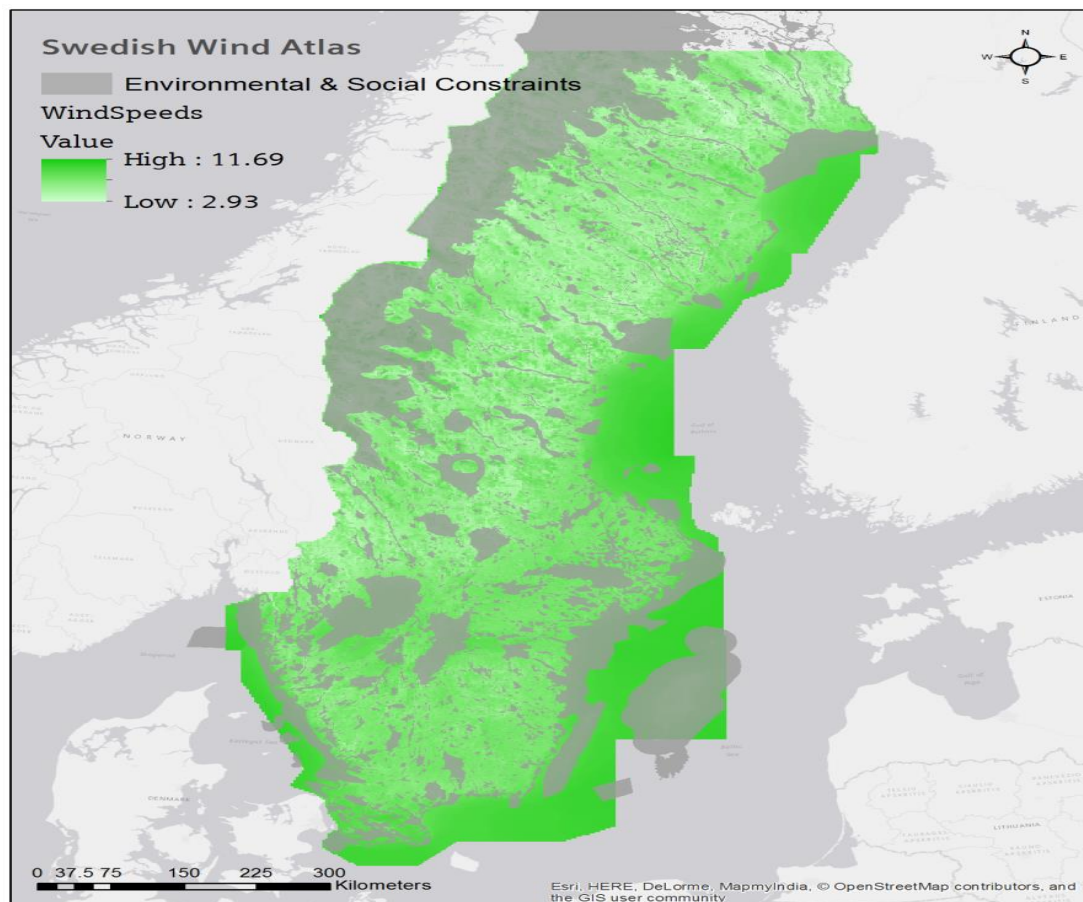
The area of the environmental constraints was determined to be 197,944 km^2, which only includes the onshore constraints. In addition, Sweden has an area of 240,649 km^2 that is based on the social and environmental constraints, including areas of tourism, cultural heritage, and the results from the qualitative studies presented in Table 35. These two categories naturally have a great deal of overlap, which has been taken into consideration in Figure 46. The third and final group of restrictions constitutes the infrastructure of Sweden, including roads, railways, and waterways adding up to 160,206 km^2. These restrictions have overlaps with the ones presented in the two previous groups. The result presented in Figure 47 reveals that especially the southern part of Sweden has large areas covered by infrastructure, making it harder to find land for onshore wind projects. At the same time,

this map represents all restrictions combined, which from a zoomed-out position does not leave much hope for future onshore wind project development in Sweden.

Figure 47 Adding infrastructure.
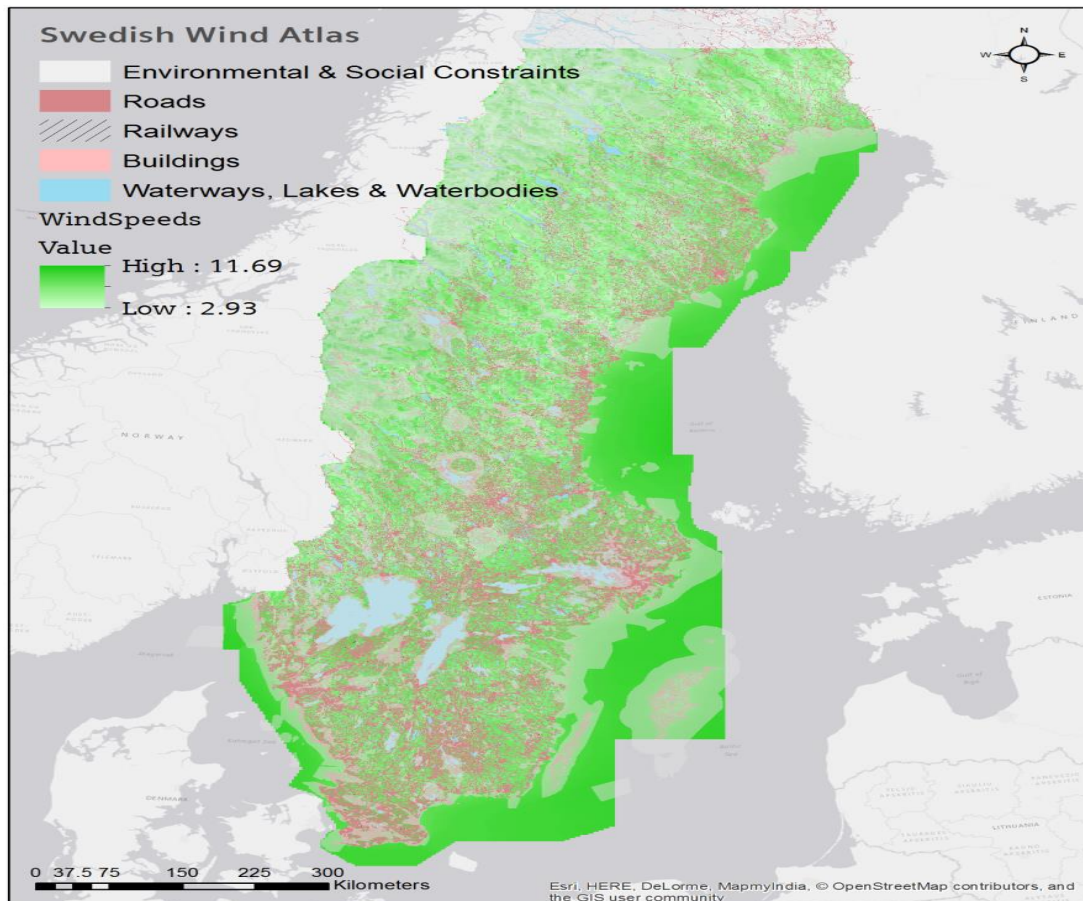
Therefore, analyses using GIS software have been carried out to determine the areas, where wind turbines legally can be constructed.

As illustrated, several restrictions are overlapping, why adding each restriction would produce a faulty conclusion of the areas suitable for wind project development. Therefore, the overlap areas were calculated using a sample presented in Table 37.

Table 37 Estimation of overlap factor

Test area to determine overlap factor	Area size in km^2	In % from total covered area
Roads (excluding minor roads such as unpaved and paths)	1,393	43%
Railways	100	3%
Waterways, lakes, and rivers (including minor overlap)	572	17%
Buildings (not all buildings are captured by OSM)	69	2%
National constraints merged	1,142	35%
Constraints in total	**3,277**	**100%**
Constraints in total (from geoprocessing)	2,325	
Constraints in total (from geoprocessing)	2,325	
Test area	3,906	
Area available (from geoprocessing)	1,580	
Area available	628	
Overlap (Δ)	952	**29% of total constraints are overlap**

In order to calculate the overlap factor, i.e., determine how many of the constraints found from different data sources are overlapping each other, a method was used to generate a percentage from the overall area size of the constraints. This method includes a test area with the size of 3,906 km^2 in the center of Sweden. Using the same layers for infrastructure, social, and environmental constraints like in the wind atlas, the amount of overlap between these layers was calculated to be 952 km^2. This means that when simply summing up all layers, the resulting covered area is 3,277 km^2, whereas when erasing from the test area, the area covered by building constraints is 2,325 km^2. The overlap of 952 km^2 is 29% of the summed up covered area (3,277 km^2), which has been illustrated in Figure 48.

Figure 48 Estimation of overlap factor.
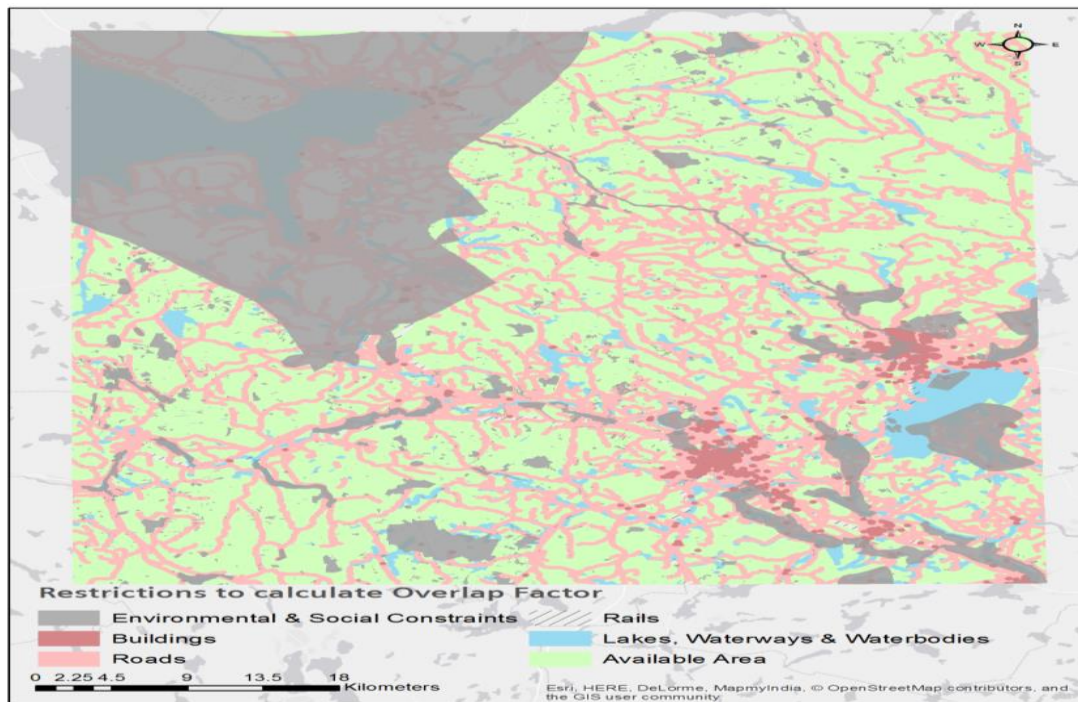
The overlap factor determined from the test sample can be used to avoid extensive computing effort caused by geoprocessing algorithms to determine the overlap of all layers applying the erasing function in GIS. Having estimated the overlap, Figure 49 presents the percentage of Sweden covered by restrictions and the remaining land left for wind project development. It is acknowledged that each region of the country differs, for which reason it is recommended to perform an overlap calculation for practical appliances.

Figure 49 Remaining area for wind project development.
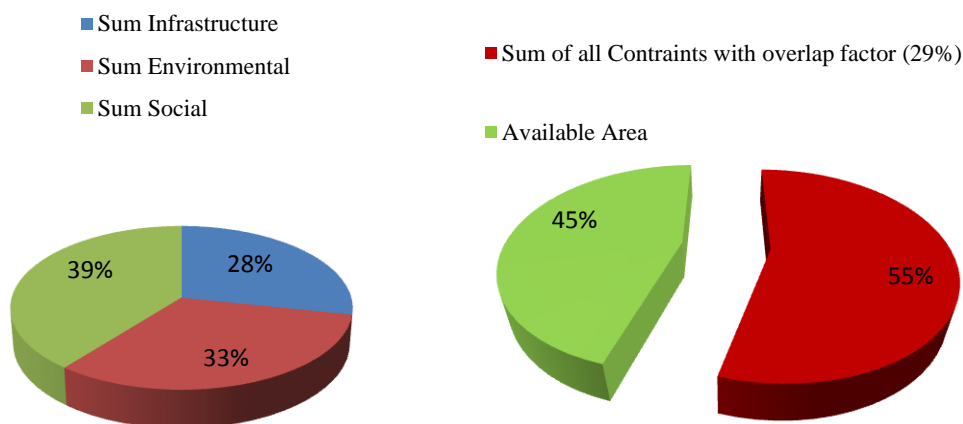
The results of the analysis revealed in Figure 49 suggest that Sweden has 204,528 km^2 left for wind project development. In continuation, it is possible to determine the number of wind turbines that can potentially be installed in Sweden. With the growing size of wind turbines, it seems fair to use a rotor diameter of 130 meters to estimate the potential amount of onshore wind turbines that can be installed across Sweden. The footprint of a wind turbine is only a few square meters; yet, a wind turbine takes up more land use due to the demands for avoiding wake effects. Two scenarios with different spacing distances between wind turbines have been presented in Table 38 below. The scenarios are based on a recent study which revealed the median minimum and median maximum spacing of more than 500 wind turbines located in onshore rural areas without forest and in onshore forested areas (Enevoldsen & Valentine, 2016), which seems to fit with the Swedish landscape.

Table 38 Three scenarios for wind turbine potential in Sweden anno 2016.

Area (km^2)	Rotor diameter/spacing horizontal distance (meters)	Number of wind turbines in Sweden
0.157	3.45/448.5	1,302,726
0.372	5.3/689	549,806

The spacing between wind turbines is usually estimated following the rotor diameter (x meters) * X. However, in order to combine the area to our results, the area measured in km^2 has also been used following:

$$(19) \qquad A = \pi \cdot r^2 = \pi \cdot (1.725 \cdot 130 \text{ m})^2 \approx \times 157,904 \text{ m}^2$$

and

$$(20) \qquad A = \pi \cdot r^2 = \pi \cdot (2.65 \cdot 130 \text{ m})^2 \approx 372,655 \text{ m}^2$$

The presented number of wind turbines is only a theoretical estimate. Yet it reveals that there are opportunities for Sweden to continue its positive development of installed wind power capacity. Another study suggested an average spacing distance equaling a land use area of 0.78 km^2 (Delucchi, et al., 2016), which would equal 262,215 wind turbines with a rotor diameter of 130 meters. However, since this particular study also included offshore wind turbines, it has not been taken into consideration.

4.2.3.3 *Practical Appliance*

The socio-technical wind atlas provides several analysis opportunities, including the enormous onshore wind power potential revealed for Sweden in this paper. Table 39 introduces additional practical opportunities using the socio-technical wind atlas for wind power purposes.

Table 39 Practical appliance of the socio-technical wind atlas

Practical appliance	Explanation
Wind resource assessment	The socio-technical wind atlas includes a wind atlas with a spatial resolution of 500. Since the mean difference between the measured wind speeds and the wind atlas was 5.4%, the atlas is considered usable for a) selecting regions with promising wind speeds, and b) using the high resolution to perform wind studies before installing a physical measurement device.
Logistic planning	The deployment of wind farms often includes infrastructural changes such as construction of roads. By using the socio-technical wind atlas, it is possible to utilize the existing road network, and, more importantly, to gain information about protected natural areas, where approvals are required before potential deforestation.
Energy policy	The development of Swedish wind power planning is very much dependent on a decentralized energy policy with municipalities impacting the decision on whether to install a wind project or not. By introducing the socio-technical wind atlas, municipalities and policymakers will have a tool to establish an overview of potentials in a specific region.
Industrial focus areas	The wind industry can gain insight into areas of specific interest in order to plan construction of factories, harbors, etc. This would naturally be a consequence of a national decision on specific areas for wind project development.

4.2.4 Conclusion

A mix of quantitative and qualitative data has resulted in the first countrywide socio-technical wind atlas. The methodology applied in this research is considered applicable for any country, and since OSM data is available in many countries, the stakeholder interviews can be conducted in any country. However, the wind data is considered unique for Sweden, both in sense of the wind atlas delivered from WeatherTech as well as the extensive amount of physical measurement devices which are considered a tremendous strength of the introduced wind atlas. The combination of the superior wind atlas and the extensive qualitative measures included in the current research enables the stakeholders of the Swedish wind industry to use and implement the findings. The results of the research further indicate that Sweden still has plenty of space remaining for wind turbines, why this cannot be the explanation of the recent decrease in the country's annually installed wind power capacity. As a concluding remark, Sweden indeed has the potential to become a world-leading wind market.

4.3 References

The following references were applied in the fifth journal article

Arnqvist, J., 2013. Mean Wind and Turbulence Conditions over Forests, Uppsala: Department of Earth Sciences Licentiate Thesis.

Arnqvist, J., Segalini, A., Dellwik, E. & Bergström, H., 2015. Wind Statistics from a Forested Landscape. Boundary-Layer Meteorology, Volume 156, p. 53–71.

Bergström, H. et al., 2013. Wind power in forests, Uppsala: Elforsk .

Chiras, D., Sagrillo, M. & Woofenden, I., 2009. Power from the Wind: Achieving Energy Independence.. 1 ed. Gabriola Island: New Society Publishers.

DEFRA, 2008. Environmental reporting guidelines , London: Department for Environment, Food and Rural Affairs.

Dellwik, E. et al., 2016. Aerial LIDAR scans for validation of CFD models in complex forested terrain. Hamburg, s.n.

Dellwik, E., Bingöl, F. & Mann, J., 2014. Flow distortion at a dense forest edge. Quarterly Journal of the Royal Meteorological Society, Volume 140, p. 676–86..

Dellwik, E., Jensen, N. & Landberg, L., 2006. Wasp in the forest.. Wind Energy.

EIA, 2016. Annual Energy Outlook 2016 With Projections to 2040, Washington D.C.: U.S. Energy Information Administration.

Ek, K., 2005. Public and private attitudes towards ''green'' electricity: the case of Swedish wind power.. Energy Policy, Volume 33 , p. 1677–1689.

Ek, K. & Persson, L., 2014. Wind farms — Where and how to place them? A choice experiment approach to measure consumer preferences for characteristics of wind farm establishments in Sweden. Ecological Economics, Volume 105, p. 193–203.

Ek, K., Persson, L., Johansson, M. & Waldo, Å., 2013. Location of Swedish wind power—Random or not? A quantitative analysis of differences in installed wind power capacity across Swedish municipalities. Energy Policy, Volume 58, p. 135–141.

Enevoldsen, P., 2016. Onshore wind energy in Northern European forests: Reviewing the risks. Renewable and Sustainable Energy Reviews, Volume 60, p. 1251–1262.

Enevoldsen, P., 2016. Wind Power in Forested Areas:Determining the Roughness Length and Displacement Height for Coniferous Trees. New Orleans, s.n.

Enevoldsen, P. & Sovacool, B. K., 2016. Examining the social acceptance of wind energy: practical guidelines for onshore wind project development in France. Renewable and Sustainable Energy Reviews, Volume 53, pp. 178-184.

Enevoldsen, P. & Valentine, S. V. .., 2016. Do onshore and offshore wind farm development patterns differ?. Energy for Sustainable Development, Volume 35, pp. 41-51.

Finnish Forest Association, 2016. www.smy.fi. [Online] Available at: http://www.smy.fi/en/forest-fi/forest-facts/finnish-forests-resources/ [Accessed 27 March 2017].

Gardiner, B., 2004. Airflow Over Forests and Forest Gaps. s.l., BWEA Tree Workshop Forestry.

Garratt, J., 1992. The Atmospheric Boundary Layer. 1st ed. s.l.:Cambridge University Press.

Gifford, J. S., Grace, R. C. & Rickerson, W. H., 2011. Renewable Energy Cost Modeling: A Toolkit for Establishing Cost-Based Incentives in the United States , Golden: NREL.

Global Wind Energy Council, 2016. Global Wind Energy Outlook 2016, Brussels: Global Wind Energy Council.

Hicks, B. B., Hyson, P. & Moore, C. J., 1975. A Study of Eddy Fluxes Over a Forest. Journal of Applied Meteorology , Volume 14.

House, J. I., Prentice, I. C. & Le Quéré, C., 2002. Maximum impacts of future reforestation or deforestation on atmospheric CO2. Global Change Biology, Volume 11, pp. 1047-1052.

IRENA, 2015. Renewable Power Generation Costs in 2014, Bonn: The International Renewable Energy Agency.

IRENA, 2016. The Power to Change: Solar and Wind Cost Reduction Potential to 2025, Bonn: The International Renewable Energy Agency .

Jacobson, M. Z. et al., 2017. 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All Sector Roadmaps for 139 countries of the World. Joule.

Lawrence, D. & Vandecar, K., 2015. Effects of tropical deforestation on climate and agriculture. Nature Climate Change , Volume 5, p. 27–36.

Lazard, 2015. Lazard's Levelized Cost of Energy Analysis Version 9.0 , New York: Lazard .

Lazard, 2016. Lazard's Levelized Cost of Energy Analysis (LCOE 10.0, New York: Larzard.

Leung, D. Y. & Yang, Y., 2012. Wind energy development and its environmental impact: A review. Renewable and Sustainable Energy Reviews , Volume 16 , p. 1031– 1039.

Möller, B., 2006. Changing wind-power landscapes: regional assessment of visual impact on land use and population in Northern Jutland, Denmark. Applied Energy , Volume 83 , p. 477–494.

Open Energy Information, 2015. Transparent Cost Database. [Online] Available at: http://en.openei.org/wiki/Transparent_Cost_Database. [Accessed 5 April 2017].

Perks, M. et al., 2010. Wind Turbines & Trees: maximising net benefit in forestry settings. Aberdeen, APF 2010 – Forestry Commission seminar series.

Pettersson, M., Ek, K., Söderholm, P. & Söderholm, K., 2010. Wind power planning and permitting: Comparative perspectives from the Nordic countries. Renewable and Sustainable Energy Reviews, Volume 14, pp. 3116 - 3123.

Raftery, P., LeBlanc, M. & Manning, J., 2004. WaSP Validation of Forestry Effects,. Glasgow, BWEA Workshop on the Influence of Trees.

Rogelj, J. et al., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, Volume 534, p. 631–639.

Scottish Government, 2016. /www.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185/17852-1/CSavings/CCguidance2-10-0. [Online] Available at: http://www.gov.scot/Topics/Business-Industry/Energy/Energy-sources/19185/17852-1/CSavings/CCguidance2-10-0[Accessed 12 May 2017].

Sovacool, B. K., 2014. Energy Studies Need Social Science. Nature, Volume 7511, pp. 529-530.

Söderholm, P., Ek, K. & Pettersson, M., 2007. Wind power development in Sweden: Global policies and local obstacles. Renewable and Sustainable Energy Reviews, Volume 11, p. 365–400.

Valentine, S. V., 2015. Wind Power Politics and Policy. 1st ed. New York: Oxford University Press.

Wang, S., Wang, S. & Smith, P., 2015. Ecological impacts of wind farms on birds: Questions, hypotheses, and research needs. Renewable and Sustainable Energy Reviews, Volume 44, pp. 599 - 607.

Warren, C. R. & McFadyen, M., 2010. Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. Land Use Policy, 27(2), pp. 204 - 213.

WAsP, 2017. www.wasp.dk. [Online] Available at: http://www.wasp.dk/[Accessed 2 January 2017].

The following references were applied in the sixth journal article

Anshelm, J. & Simon, H., 2016. Power production and environmental opinions – Environmentally motivated resistance to wind power in Sweden. Renewable and Sustainable Energy Reviews , Volume 57 , p. 1545–1555.

Bergek, A. &. J. S., 2010. Are Tradable Green Certificates a Cost-efficient Policy Driving Technical Change or a Rent-generating Machine? Lessons from Sweden 2003-2008. Energy Policy, Volume 38, pp. 1255-1271.

Carlman, I., 1988 . Wind Power in Denmark! Wind Power in Sweden?. Journal of Wind Engineering and Industrial Aerodynamics , Volume 27 , pp. 337-345.

Countrymeters, 2016. www.countrymeters.info/en/Sweden. [Online] [Accessed 21 July 2016].

Darmani, A., 2015. Renewable energy investors in Sweden: A cross-subsector analysis of dynamic capabilities. Utilities Policy, Volume 37, pp. 46-57.

Delucchi, M. A. et al., 2016. Spreadsheets for 139-country 100% wind, water, and solar roadmaps. [Online]

Available at: http://web.stanford.edu/group/efmh/jacobson/Articles/I/WWS-50-USState-plans.html

[Accessed 2 July 2016].

Ejdemo, T. & Söderholm, P., 2015. Wind power, regional development and benefit-sharing: The case of Northern Sweden. Renewable and Sustainable Energy Reviews , Volume 47 , p. 476–485.

Ek, K. & Matti, S., 2015. Valuing the local impacts of a large scale wind power establishment in northern Sweden: public and private preferences toward economic, environmental and sociocultural values. Journal of Environmental Planning and Management, Volume 58, pp. 1327-1345.

Ek, K. & Persson, L., 2014. Wind farms — Where and how to place them? A choice experiment approach to measure consumer preferences for characteristics of wind farm establishments in Sweden. Ecological Economics, Volume 105, p. 193–203.

Enevoldsen, P., 2016. Onshore wind energy in Northern European forests: Reviewing the risks. Renewable and Sustainable Energy Reviews, Volume 60, p. 1251–1262.

Enevoldsen, P., 2016. Wind Power in Forested Areas: Determining the Roughness Length and Displacement Height for Coniferous Trees. New Orleans, s.n.

Enevoldsen, P. & Sovacool, B. K., 2016. Examining the social acceptance of wind energy: practical guidelines for onshore wind project development in France. Renewable and Sustainable Energy Reviews, Volume 53, pp. 178-184.

Enevoldsen, P., Sovacool, B. K. & Tambo, T., 2014. Collaborate, involve, or defend? A critical stakeholder assessment and strategy for the Danish hydrogen electrolysis industry. International Journal of Hydrogen Energy, Volume 39, p. 20879–20887.

Enevoldsen, P. & Valentine, S. V., 2016. Do onshore and offshore wind farm development patterns differ?. Energy for Sustainable Development.

Geofabrik, 2016. www.geofabrik.de. [Online] [Accessed 20 July 2016].

González-Longatt, F., González, J. S., Payán, M. B. & Santos, J. M. R., 2014. Wind-resource atlas of Venezuela based on on-site anemometry observation. Renewable and Sustainable Energy Reviews, Volume 39 , p. 898–911.

Gullberg, A. T. & Bang, G., 2015. Look to Sweden: The Making of a New Renewable Energy Support Scheme in Norway. Scandinavian Political Studies, Volume 38 .

Länsstyrelsen, 2016. www.lansstyrelsen.se. [Online]

[Accessed 8 August 2016].

Meyer, N. I., 2007. Learning from Wind Energy Policy in the EU: Lessons from Denmark, Sweden and Spain. European Environment, Volume 17, p. 347–362.

Mortensen, N. G. et al., 2006. WIND ATLAS FOR EGYPT: MEASUREMENTS, MICRO- AND MESOSCALE MODELLING, Brussels : EWEA.

Nawri, N. P. G. N. et al., 2014. The wind energy potential of Iceland. Renewable Energy, Volume 69 , pp. 290-299.

Noorollahi, Y., Mohammadi, H. & Yousefi, M., 2016. Multi-criteria decision support system for wind farm site selection using GIS. Sustainable Energy Technologies and Assessments, Volume 13, p. 38–50.

Pettersson, M., 2008. Renewable Energy Development and the Function of Law:A Comparative Study of Legal Rules Related to the Planning, Installation and Operation of Windmills, Luleå: Luleå University.

Pettersson, M., Ek, K., Söderholm, P. & Söderholm, K., 2010. Wind power planning and permitting: Comparative perspectives from the Nordic countries. Renewable and Sustainable Energy Reviews, Volume 14, pp. 3116 - 3123.

Sliz-Szkliniarz, B. & Vogt, J., 2011. GIS-based approach for the evaluation of wind energy potential: a case study for the Kujawskoe Pomorskie Voivodeship. Renewable Sustainable Energy Reviews , Volume 15, pp. 696-707.

Sovacool, B. K. & Brossmann, B., 2010. Symbolic convergence and the hydrogen economy. Energy Policy, Volume 38, p. 1999–2012.

Swedish Forest Agency, 2014. Swedish Statistical Yearbook of Forestry 2014, Jönköping: Skogsstyrelsen - Swedish Forest Agency.

Szarka, J., 2007. Why is there no wind rush in France?. European Environment , Volume 17, p. 321–333.

The Wind Power Net, 2016. www.thewindpower.net. [Online] Available at:
http://www.thewindpower.net/country_en_17_sweden.php [Accessed 2 April 2016].

Warren, C. & McFadyen, M., 2010. Does community ownership affect public attitudes to wind energy? A case study from south-west Scotland. Land Use Policy, Volume 27, p. 204–213.

5 Design principles to limit the risks of siting wind turbines in Northern European forests

The concluding chapter of this dissertation integrates and reflects upon the main findings in the six journal articles by examining the answers given for each of the three research questions, in order to answer the main problem formulation "**What design principles limit the risks of siting wind turbines in Northern European forests?**". The conclusion therefore summarizes the output from the six journal articles and other work conducted throughout the industrial PhD project 4135-00033B.

It is furthermore sought to address the outlook and future research of wind power expansion in the forested areas described.

5.1   Revealing the specifications of wind power in forested areas

The second chapter of this dissertation introduced two journal articles to answer the first research question: *What are the specifications of wind projects in forested areas?* In so doing, the first article introduced some of the generic patterns of wind farms located in forested areas, which are listed below:

- The datasets introduced in Chapter 2 found that wind projects developed in forested areas consist of smaller wind farms (median of 36 MW installed wind power), and thereby also a lower cumulative wind farm production (MWh) than other onshore projects.

- Contrary to expectations, onshore forested wind farms produced, on average, more energy per installed MW than other onshore projects and exhibited far lower variance in power output than the other on- and offshore wind projects in the datasets.

- Wind projects developed in forested areas have a lower minimum spacing than the average onshore wind projects; however, the projects in forests are also developed with a lower maximum spacing than the remaining onshore projects.

- Wind farms in forests can be developed in a more concentrated manner and still produce a more consistent power output portfolio than offshore wind farms.

- While the development of wind projects in forested areas is still in its infancy in most areas, it is more prone to being installed in more mature markets than those where onshore projects are introduced to rural areas.

When only investigating the output from the first journal article, it can be concluded that the wind turbines deployed in forested areas are performing just as well, and sometimes even better, than the other onshore wind turbines. However, as mentioned in the concluding remarks of the paper, wind farms

located in forested areas should be the subject of further examination. The reason for this is that the majority of the wind farms operating in forest areas are geographically located in Sweden and the UK. As presented in Archer and Jacobson (2005) and Troen and Petersen, (1989), the two countries have ideal wind conditions, with the strongest winds being in the UK, and Swedish projects often sited with a hub height above 115 meters, ensuring greater wind speeds. By comparison, many of the onshore projects in the datasets were located in central Europe, the US, and China and were operating with lower hub heights and less favorable wind speeds. Furthermore, the articles dealt with some of the other differences such as spacing and learning effects, where wind turbines located in forested areas can be claimed to be a novel configuration. Therefore, the literature does not currently provide an overview of the challenges and potential solutions for the increasing risks of deploying wind turbines in forests, which is why the second journal article focused on framing this issue.

The second journal article introduced some of the generic patterns of wind farms located in forested areas, which are listed below:

- A risk framework can be constructed for onshore wind projects sited in forested areas by introducing 10 generic risk factors across three phases during a wind project's lifetime.

- A novel approach to conduct comparative analyses of the relationship between the development of a technology and the development of scholarship was introduced. This relationship indicated that a higher installed capacity equals more academic contribution for a specific country.

- Academic publications targeting wind power in forested areas in Northern Europe tend to focus on resource assessments; thereafter studies related to land use, social opposition, cost overrun and environmental degradation.

- Despite several publications few, if any, of the risks associated with wind turbines in forested areas have been sufficiently covered. An important reason for this lack of literature coverage is most likely due to the novelty of the configuration.

- There is an academic consensus that the greatest risk concern was embedded in the resource assessment and the estimation of wind conditions.

The second journal article presented in Chapter 2 introduced, as of 2016, the most comprehensive literature review on wind turbines in forested areas. Besides introducing a risk framework not only applicable in Northern Europe and for wind projects in forested areas, but also generally for all onshore wind projects, the paper also analyzed the gaps in literature and, furthermore, trends in literature when covering risks in wind projects. It was not a surprise that the risks in the decommission phase were not yet covered, as no one has, to date, encountered those risks. Moreover, it became clear that the wind industry and academia are facing great challenges in regards to the development phase, which impacts upon the operational phase and thereby the levelized cost of energy and the entire business case.

5.1.1 Other Perspectives on Research Question 1

Other studies were carried out throughout the Industrial PhD project 4135-00033B, which brings clarity to Research Question 1. In Sovacool, et al. (2016) more than 11 GWs of installed wind power capacity

was examined in order to investigate the risk of cost overrun and underrun during the construction of onshore and offshore wind farms. It was discovered that the majority of onshore wind farms exhibited a cost underrun, although with a mean cost escalation of 0.8%; however, a median of -0.5 would indicate cost underrun. The offshore wind farms experienced a mean cost escalation of 9.6%, and a median cost overrun of 5.7%. This study did not consider wind farms in forested areas as a unique configuration. However, considering a worst-case scenario at 1.0% for projects in forests, and thereby determining a cost overrun far from the median, and comparing the performance of such projects to offshore projects revealed in the first two journal articles of this dissertation, it can be concluded that wind projects in forested areas have great potential providing the risk associated with resource assessment is managed. The potential of overcoming such a barrier is expected to be supported from the innovative transitions of wind power, which are previously and currently taking place in Northern Europe, something which was elaborated in Sovacool and Enevoldsen (2015) where the innovative styles of Siemens Wind Power and Vestas were examined, revealing remarkable skills to overcome barriers related to the introduction of wind farms in new climates and topographies. The findings discovered when answering Research Question 1 also contributed to the study by Jacobson, et al. (2017), where roadmaps to transform the all-purpose energy infrastructures of 139 countries to those powered by wind, water, and sunlight have been developed. The potential and spacing requirements of wind projects in forested areas have allowed for more areas to be considered viable for wind project development in this study, and hopefully in the future studies and energy planning policies. The framework applied in the second journal article was furthermore inspired by a previous model presented at a conference, where it was revealed that wind projects can be divided into such risk parameters (Enevoldsen, 2015).

5.2   The risks of siting wind turbines in forested areas

The third chapter of this dissertation introduced two journal articles in order to answer the second research question: *How can the risks associated with the siting of wind turbines be limited?*

The third journal article examined the social opposition of onshore wind power. The second journal article found that social opposition is a major risk for onshore wind project development in forested areas. In the third journal article an empirical data collection was carried out through interviews with seven stakeholder groups in the wind industry. The outcome of the interviews was triangulated with the output of a literature review, which sought to theorize social acceptance and opposition of onshore wind power. The main findings from this research are listed below.

- Social opposition may cause cost escalations and delays during the development of a wind project, and in some cases even reject a wind project. The impact of social opposition increases the LCOE of onshore wind power.

- Negative impact on flora and fauna as a consequence of deforestation may increase social opposition during the construction phase of a wind project.

- The impact from noise and flicker effects remained the greatest reason for social opposition. The complaints related to these parameters tend to increase with an increasing number of wind turbines. Especially if the layout of the wind farm has been determined without any public involvement.

- Negative impact on socioeconomic parameters will lead to opposition, e.g. if an area is well-known to tourists for its wildlife and/or nature.

- It is considered an advantage to involve local decision makers in beginning of the construction phase, especially in countries with decentralized political systems (Such as Sweden).

- If possible, the wind industry should aim at creating local socioeconomic gains, as this is the key parameter for social acceptance. Such can be created through local labor and/or attractive investment opportunities in an early stage of the construction phase.

The third journal article introduced a guideline on when to apply certain actions and conduct certain activities in the development of a wind project. This guideline is expected to cover all onshore wind projects, and not only the ones developed in forested areas. The conclusions of this article have been applied in the fifth and sixth journal article, when managing the risks of onshore wind project development in forested areas. However, as stated in the second journal article, the greatest risk seemed to be resource assessment, which, despite several approaches, was nonetheless lacking a uniform approach. Such an approach was sought to be introduced in the fourth journal article of this PhD dissertation. This examined online available land use models in a comparison with the developed ORA, where it was discovered that linearized models for wind estimations can provide reliable resource assessments in forested areas only by converting tree heights into roughness lengths, whilst applying a displacement height factor. The main findings from this research are listed below:

- Tree height information can be considered a minimum requirement for estimations of wind conditions in forested areas.

- Fixed roughness lengths based on land use classes tend to underestimate the impact from forestry on wind conditions.

- Using ORA provides better results than online roughness maps, even when applying a low spatial resolution for ORA (1000 meters).

- Displacement Heights are generally applicable for assessments where forest data is provided in high resolution.

- It is suggested that ORA is used for estimating wind conditions when no on-site laser scans have been carried out.

In conjunction with this, the fourth journal article introduced an approach which is easily implementable and without major requirements for data input. The ORA method is currently being implemented as a standard part in three different commercial software programs for the estimation of wind conditions (WindSim, WindPRO, and WAsP).

5.2.1 Other Perspectives on Research Question 2

Other studies were carried out throughout the Industrial PhD project 4135-00033B, which brings clarity to Research Question 2.

The third article sought to understand the social acceptance of wind projects in forested areas. Several of those reasons were applied in the fifth and sixth journal article of this dissertation, where it can be concluded that public acceptance from an academic point of view has, as of 2016, been perceived as being more or less the same in forested and non-forested areas. The output from the third journal article was furthermore applied when examining the possibility of installing an integrated power system based on one of the Faroe Islands (Enevoldsen & Sovacool, 2016). Despite the impact of social opposition, the resource assessment of wind conditions above forest canopies in Northern Europe remained the most severe risk criteria, which is why several studies were conducted on that topic.

The development of the ORA was based on two studies where a suggestion for a uniform roughness and displacement height approach has been suggested by comparing different academic contributions on roughness length and displacement height approaches with wind profiles measured from 22 meteorological masts in forested areas (Enevoldsen, 2016b; Enevoldsen, 2016c), the reason being was the diversity of the proposed approaches, which differed significantly when examining various potential solutions. From Hicks, et al. (1975), who analyzed wind measurements in a forest, the roughness length (Z_0) could be calculated using 0.3(h-d), where h is the tree height and d is the displacement height, which is why this method very much depends on the approach for estimating the displacement height to Freris (1990) who found that Z_0 can be calculated as h/30. A more comprehensive study was carried out by Jarvis, et al. (1976), who tested data from 11 forests resulting in z0 as 0.075*h. A more conservative suggestion came from Garratt (1992) who recommended 01.*h. Table 40 sums up the different academic contributions on roughness length approaches.

Table 40 Division of roughness length approaches

Reference	Tree Type	Roughness Length
Hicks, et al. (1975)	Coniferous	0.3*(h-d)
Freris (1990)	Coniferous	h/30
Garratt (1992)	Coniferous	0.1*h
Jarvis, et al. (1976)	Coniferous	0.075*h

As presented in Table 40, the approach for calculating the roughness length of different tree types differs greatly, which can have consequences for estimations of the wind turbines' operational efficiency in forests. Furthermore, for studies related to Northern Europe, though using roughness lengths and discussing these, none of the above-cited studies have, to date, comprehensively studied the roughness length of different forest types in Northern Europe. ORA used the approach of Hicks, et al. (1975), yet it was discovered that the displacement height d could add certainty to the estimation above homogenous forest canopies. Based on (21), where Umean is the mean wind speed at a certain height, Z. U* is the friction velocity, κ is the von Kármán constant (0.40), Z the height above ground level, it can be derived that the roughness length will lower as the displacement height is increased

(21)
$$\text{Umean (Z)} = U_* * \frac{1}{\kappa}\text{LN}\left[\frac{z-d}{z_0}\right]$$

The relationship between the roughness length and the displacement was obtained from a case study site in Sweden (Enevoldsen, 2016), and has been mapped in Figure 50 below.

Figure 50 Mapping the relationship between roughness length and displacement height (Enevoldsen, 2016)
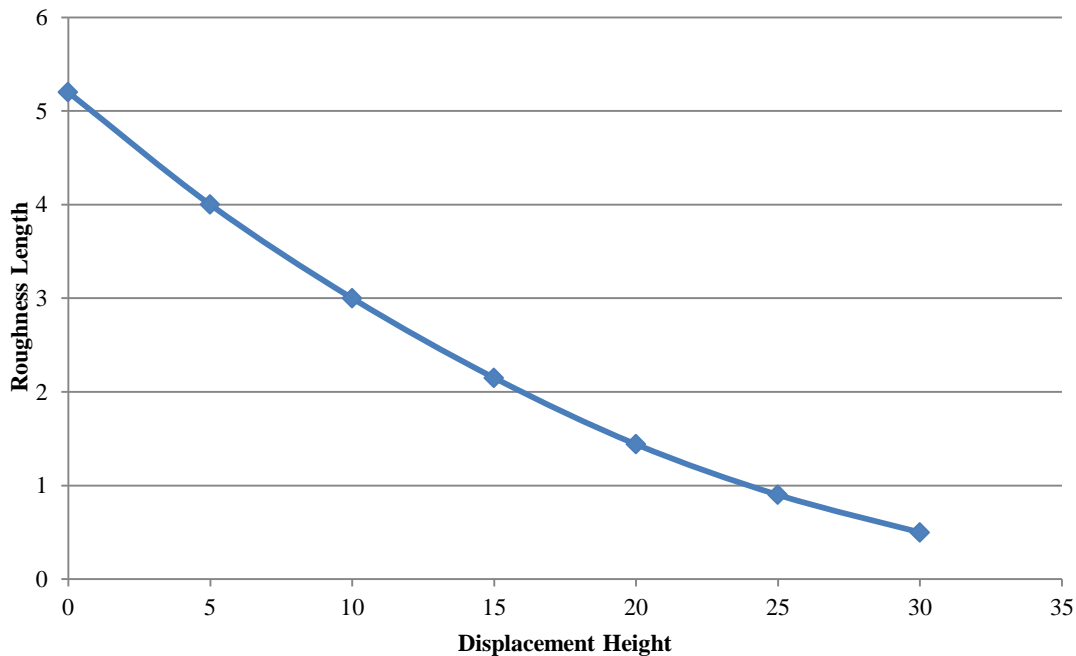
The displacement height is an important parameter when conducting resource assessments in forested areas. As regards low vegetation and small obstacles, the surface layer starts at ground level (z_0); however, above homogenous dense forests, the surface layer begins at a greater height, at a distance, d, which is referred to in wind simulation terms as the displacement height. As with the academic contributions for roughness length estimations, scholars have different suggestions for how to estimate the displacement height. The main part of the estimations was defined in the same studies as those that defined the roughness length approach. For instance, Garratt (1992) defined the displacement height as 2*h/3, Jarvis, et al. (1976) found an average in their studies of 0.78*h and Hicks, et al (1975) estimated an approach close to Jarvis, et al. (1976) by using 0.8*h. By studying low vegetation up to tall trees, Stanhill (1969) found an approach using 0.64*h. Raupach and Thom (1981) examined forest canopies only, and determined 0.65*h. Dolman (1986) proposed 0.75*h. The different approaches for establishing displacement heights have been presented in Table 41.

Table 41 Division of displacement height approaches

Author	Tree Type	Displacement Height
Raupach and Thom (1975)	Coniferous	0.65*h
Dolman (1986)	Coniferous	0.75*h
Garratt (1994)	Coniferous	2*h/3
Stanhill (1969)	Coniferous	0.64*h
Jarvis, et al. (1976)	Coniferous	0.78*h
Hicks, et al (1975)	Coniferous	0.8*h

174

By conducting several case studies all across Northern Europe, it was discovered through statistical analyses that a modified version of Garrat (1994) for the displacement height and Hicks, et al. (1975) resulted in the best fit.

In Enevoldsen (2017), ORA was validated, and further tested against more sophisticated forest models using CFD software. The results indicated that using standardized CFD forest models will provide less reliable results than that produced combining ORA with a linearized solver, in this case WAsP. The bars in Figure 51 below illustrate the difference between ORA and three commercial CFD software programs, where the estimated wind speed (m/s) at seven positions in a forest was compared to that measured by a meteorological mast at each position.

Figure 51 Comparative analysis of ORA versus commercial CFD software
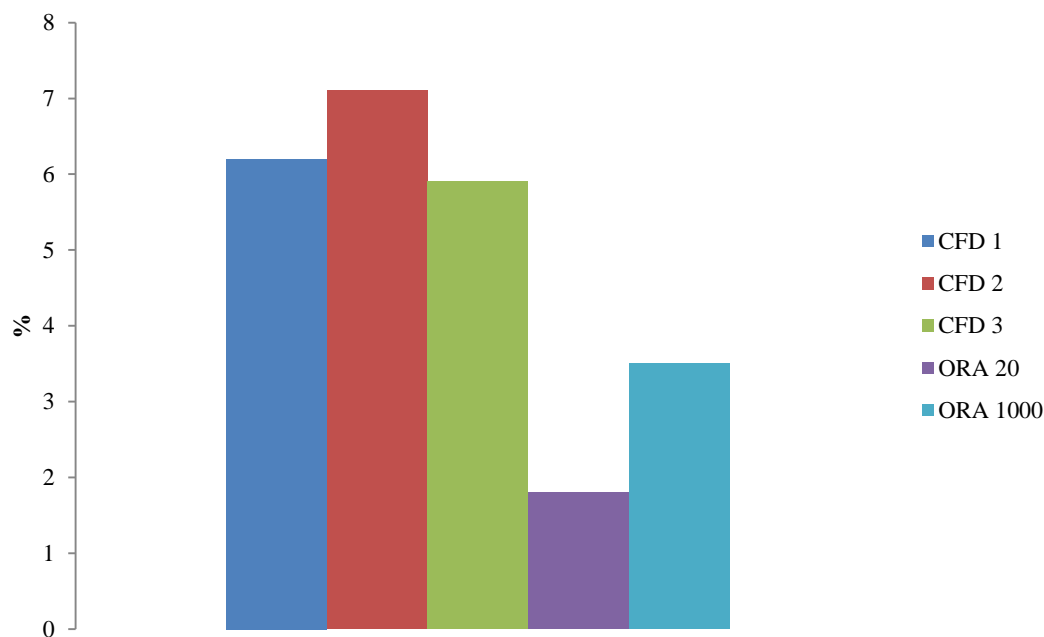
The same study also proved that ORA provides reliable results using different spatial resolutions, which, in Figure 51, was illustrated by showing the difference between the estimated and measured wind speed (m/s) for a spatial resolution of 20 and 1000 meters using ORA. Dellwik, et al. (2016) explained that numerical forest models often require a certain data input which exceeds the tree height demands required by ORA. When using airborne laser scans to measure the density of forests, numerical models can provide results in the same range as ORA, and most likely even more precise ones. It is recommended that such comparisons are to be carried out in the near future, where remote sensing data such as the leaf area indexes provided by the Copernicus satellite program (Copernicus, 2017) is expected to increase the dataflow to forest models in CFD software. Ivanell, et al. (2017) examined various forests models where a combination of WAsP and ORA produced results similar to the best numerical models in the industry, which either applies Reynolds-averaged Navier–Stokes equations (RANS) as the three commercial CFD solvers in Figure 50 or Large Eddy Simulations (LES), where both have proved excellent in detecting turbulence structures for a range of industries.

5.3 Managing the risks of wind project development in forested areas

The fourth chapter of this dissertation introduced two journal articles to answer the third research question: *What is the best approach to managing the risks of wind project development in Northern European forests?* In so doing, the articles introduced some of the approaches which can be applied to limit the risks for deployment of wind farms located in forested areas. The key findings are listed below:

- Deforestation only has a minor impact on the performance of the wind turbine, and in some cases it can be preferable to fell fewer trees, unless there is the chance of clearcutting an area of 23 hectares.

- It is possible to achieve CO_2 savings despite the deforestation, due to the increased annual energy production from a renewable source. However, more deforestation does not result in sufficient additional energy to defend the deforestation of a larger area.

- When ensuring the development of wind farms in plantations instead of natural forests, social opposition is decreased.

- If timber can be sold from the deforestation, the increased annual energy production and income from timber will result in a lower levelized cost of energy after deforestation. However, without income from timber, the deforestation should be kept at a minimum.

- It is possible to construct socio-technical wind atlases for each of the targeted countries when applying open street data, interviews and mesoscale wind data.

- When introducing a modern multi-megawatt wind turbine suitable for siting in forested areas, Sweden has a theoretical area which would allow the installation of more than 500,000 wind turbines without interfering with any hard or soft restrictions.

5.3.1 Other Perspectives on Research Question 3

Other studies were carried out throughout the Industrial PhD project number 4135-00033B, which brings clarity to Research Question 3. Obviously, the work conducted in relation to the two first research questions had an impact on the construction of the answer to the third. In addition to the introduced papers, the fifth journal article was inspired by the findings in Sovacool, et al. (2015) where the environmental profit and loss was examined for two wind turbine sites in Northern Europe. It was discovered that, from a purely environmental standpoint, offshore steel turbines have the best budget for Environmental profit and loss (EP&L)—the least losses—followed by onshore turbines with offshore concrete turbines having the worst EP&L. However, these results would perhaps have differed if including the environmental losses of deforestation. Nevertheless, such an estimation could be implemented for each siting process of wind turbines in forested areas, which could then be included in the overall environmental budget for a wind project.

The interviews conducted in both articles were inspired by the third journal article on social acceptance by Enevoldsen and Sovacool (2016) where synthetic reasons for social opposition to wind project were introduced.

The stakeholders' approach applied in journal articles five and six was inspired by Enevoldsen, et al. (2014) who presented a method for detecting and analyzing stakeholders related to the Danish hydrogen industry, which was transferred to stakeholders in the Northern European wind industry in forested areas. In relation to hydrogen, and the potential outlook from the sixth journal article, a method for optimizing wind farm investments using hydrogen as a potential storage technology and off-take proved to increase the return on investment significantly (Hou, et al., 2017). The optimization method was based on a study by Enevoldsen and Sovacool (2016) where an integrated power system consisting of wind and hydrogen was examined at one of the Faroe Islands, resulting in a conclusion that this would be capable of delivering stable energy to the inhabitants on the island. When considering the population density of the targeted countries in this dissertation, and the rurality of Northern Sweden and Norway, such an integrated power system could be considered and potentially incorporated into a socio-technical renewable energy atlas.

5.4 Outlook

The contribution of the industrial PhD project 4135-00033B during the period 2014-2017 can be rated by verifying the impacts on future wind project development and operation in Northern European forested areas. However, that would require observations over a period of 1-30 years when including the project development time and operational life time of a modern multi-megawatt wind turbine.

It is therefore more interesting to observe the current impact of the research conducted in relation to the Industrial PhD project 4135-00033B, as Siemens Gamesa Renewable Energy internally has a broader focus on the impact on forestry, and also more important solutions to occurring risks when compared to the situation in 2014. The latter is necessary as the research revealed risks of which the company and industry were still unaware. These risks included an overview of the performance and global trends of wind power located in forests compared to other onshore locations and the offshore location, which has several similarities to the forested configuration. This was the first part of showing that wind projects in forested areas are to be considered an individual wind power configuration. Most stakeholders in the industry would also have agreed in 2014 that wind turbines in forested areas needed to be taller due to the natural presence of surface objects; however, few, if any, would be aware of the fact that well-studied phenomena such as social opposition and the environmental impact would differ from other onshore projects. The increasing risk parameter, social opposition, actually decreases when ensuring installations of wind turbines in industrial forest plantations, which can furthermore add financial value to the wind project and/or the local businesses, due to income from timber and/or bio pallets etc. These assumptions need to be furthermore tested and validated to support the interdisciplinary business opportunity of minimizing risks in the wind industry, meanwhile ensuring financial profit in the forest industry.

Nevertheless, the introduction of strategies for managing other risks, along with the overestimation of the performance of wind turbines in forested areas, became an emergent topic throughout the PhD study, which is why several solutions were discussed and introduced. The first solution was as simple as ORA, from where siting engineers had to rely on tree height maps instead of roughness maps based on land use classes. The output was a method which significantly decreased the mean bias of wind resource assessments and was further implemented in Siemens Gamesa Renewable Energy and also in various software programs applied in the industry. WindPRO, the software from where some of the most popular

online available roughness maps can be downloaded, is currently changing their recommendations to apply ORA for all simulations of wind resources, and WindSim, a commercial CFD software, is implementing a method for creating roughness maps. The verification of the solver was carried out with researchers from the DTU, and the approach is further being tested as part of the integration of terrain maps in WAsP. In addition to ORA, an approach for collecting and converting data applicable for numerical solvers in forested areas was derived using the latest satellite data, and a global database was constructed for that exact purpose. A presentation at the annual European wind energy conference is expected to reveal the impact of that database. As mentioned, future studies and observations will reveal the true impact of these approaches, although the preliminary results are promising.

The socio-technical studies seem to be a new trend in wind engineering, as the industry and academia have realized that social factors can be equally important for the development of a wind project in forested areas. The maps provided in the sixth paper have to be verified by future wind project developments, as it is sought to publish them and make them available as open source for developers, in order to save time and resources in the search for appropriate site locations. Another interesting spin-off is the potential to construct such maps for other countries, and include other technologies, in order to make detailed plans for powering the globe by renewables.

To conclude, this PhD dissertation has revealed the risks associated with wind project development in Northern European forests by examining the performance of operating wind turbines and analyzing the existing literature related to the topic. Consequently, approaches for limiting and predicting the most severe risks have been introduced and implemented into Siemens Gamesa Renewable Energy and the wind industry. Finally, it has been proven that it is possible to merge interdisciplinary scientific approaches, which ultimately brings additional value to the management of wind projects in Northern European markets dominated by forests. It is therefore believed that the impact of this dissertation will make it easier and smoother to expand the installed wind power capacity in the targeted markets. A vision, however, can only be verified when examining the performance over a wind turbine lifetime.

5.5 References

The following material published or submitted in the Industrial PhD number 4135-00033B was applied for the perspectives on the first research question.

Enevoldsen, Peter. / Onshore wind energy in forested areas in Northern Europe: Reviewing the risk. / Journal of Cleaner Production, 2015.

Jacobson, Mark Z. ; Delucchi, Mark A.; Bauer, Zack A.F.; Goodman, Savannah C.; Chapman, William E.; Cameron, Mary A.; Bozonnat, Cedric; Chobadi, Liat; Clonts, Hailey A.; Enevoldsen, Peter; Erwin, Jenny R.; Fobi, Simone N.; Goldstrom, Owen K.; Harrison, Sophie H.; Hennessy, Nora M.; Kwasnik, Ted M.; Liu, Jingyi; Lo, Jonathan; Meyer, Clayton B.; Morris, Sean B.; Moy, Kevin R.; O'Neill, Patrick L.; Petkov, Evan; Redfern, Stephanie; Schucker, Robin; Sontag, Mike A.; Wang, Jingfan; Weiner, Eric; Yachanin, Alex S. / 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. / Joule. 2017

Sovacool, Benjamin; Enevoldsen, Peter; Koch, Christian; Barthelmie, Rebecca J. / Cost performance and risk in the construction of offshore and onshore wind farms. / Wind Energy, 2016.

Sovacool, Benjamin; Enevoldsen, Peter. /One style to build them all: Corporate culture and innovation in the offshore wind industry. Energy Policy, Vol. 86, 11.2015, s. 402-415.

The following material published or submitted in the Industrial PhD 4135-00033B was applied for the perspectives on the second research question.

Dellwik, Ebba; Arnqvist, F Johan; Cavar, Dalibor; Enevoldsen, Peter; van der Laan, Paul. / Aerial LIDAR scans for validation of CFD models in complex forested terrain. / 2016. Abstract from WindEurope, Hamburg, Germany.

Enevoldsen, Peter. 2017. / A Uniform Approach for Wind Simulations in Forested Areas: Examining the Importance of Data Inputs. / Abstract from WindEurope Resource Assessment 2017.

Enevoldsen, Peter. / Addressing the Challenge of Determining Wind Conditions in Forests Dominated by Coniferous Trees. / North American Clean Energy , Vol. 10, No. 4, 2016.

Enevoldsen, Peter / Wind Power in Forested Areas: Determining the Roughness Length and Displacement Height for Coniferous Trees. / . 2016. Poster session presented at AWEA, New Orleans, USA.

Integrating power systems for remote island energy supply: Lessons from Mykines, Faroe Islands. / Enevoldsen, Peter; Sovacool, Benjamin. I: Renewable Energy, Vol. 85, 2016, s. 642–648.

Ivanell, Stefan; Arnqvist, Johan; Witha, Björn; Avila, Matias; Cavar, Dalibor; Chavez Arroyo, Roberto A.; Dellwik, Ebba; Enevoldsen, Peter; Espinosa, Hugo Olivares; Peralta, Carlos. / A forested site modelled with different microscale model approaches. / Abstract from Wind Energy Science Conference 2017.

The following references were applied as supplemental material for the perspectives on the second research question

Dolman, A., 1986 . Estimates of roughness length and zero plane displacement for a foliated and non-foliated oak canopy. Agricultural and Forst Meteorology, Volume 36 , pp. 241-248.

Freris, L. L., 1990. Wind energy conversion systems. s.l.:Prentice Hall.

Garratt, J., 1992. The Atmospheric Boundary Layer. 1st ed. s.l.:Cambridge University Press.

Hicks, B. B., Hyson, P. & Moore, C. J., 1975. A Study of Eddy Fluxes Over a Forest. Journal of Applied Meteorology , Volume 14.

Jarvis, P. G., James, G. B. & Landsberg, J. J., 1976. Coniferous Forest. Vegetation and the Atmosphere, Volume 2, pp. 171-240.

Raupach, M. & Thom, A., 1981. Turbulence in and above Plant Canopies.. Annual Review of Fluid Mechanics , Volume 13, pp. 97-129.

Stanhill, G., 1969. A Simple Instrument for the Field Measurement of a Turbulent Diffusion Flux. Journal of Applied Meteorology, Volume 8, pp. 509-513.

The following material published or submitted in the Industrial PhD 4135-00033B were applied for the perspectives on the third research question.

Collaborate, Involve, or Defend? A Critical Stakeholder Assessment and Strategy for the Danish Hydrogen Electrolysis Industry. / Enevoldsen, Peter; Sovacool, Benjamin; Tambo, Torben. /International Journal of Hydrogen Energy, Vol. 39, Nr. 36, 12.12.2014, s. 20879–20887.

Integrating power systems for remote island energy supply: Lessons from Mykines, Faroe Islands. / Enevoldsen, Peter; Sovacool, Benjamin. I: Renewable Energy, Vol. 85, 2016, s. 642–648

Optimizing Investments in Coupled Offshore Wind -Electrolytic Hydrogen Storage Systems in Denmark. / Hou, Peng; Enevoldsen, Peter; Eichman, Joshua; Hu, Weihao; Jacobson, Mark; Chen, Zhe. Journal of Power Sources. 2017

Valuing the manufacturing externalities of wind energy: Assessing the environmental profit and loss of wind turbines in Northern Europe. / Sovacool, Benjamin; Perea, Mario Alberto Munoz ; Matamoros, Alfredo Villa; Enevoldsen, Peter. / Wind Energy, Vol. 19, Nr. 9, 02.11.2015, s. 1623–1647.

6 Appendix

6.1 Other contributions to the Industrial PhD project 4135-00033B

The following presents the published and submitted materials by the applicant as of 24/7/2017. The contributions are divided into published and submitted material and further structured by the type of publication. The journal articles have been divided according to the Danish Bibliometric Research Indicator

Published Journal Articles - Danish Bibliometric Research Indicator 2

1. Onshore wind energy in Northern European forests: Reviewing the risks. / Enevoldsen, Peter. / Renewable & Sustainable Energy Reviews, Vol. 60, 2016, s. 1251–1262. / DOI: 10.1016/j.rser.2016.02.027

2. Cost performance and risk in the construction of offshore and onshore wind farms. / Sovacool, Benjamin; Enevoldsen, Peter; Koch, Christian; Barthelmie, Rebecca J. / Wind Energy, 2016. / DOI: 10.1002/we.2069

3. Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France. / Enevoldsen, Peter; Sovacool, Benjamin. I: Renewable & Sustainable Energy Reviews, Vol. 53, 01.2016, s. 178-184. / DOI: 10.1016/j.rser.2015.08.041

4. One style to build them all: Corporate culture and innovation in the offshore wind industry. / Sovacool, Benjamin; Enevoldsen, Peter. /Energy Policy, Vol. 86, 11.2015, s. 402-415. /DOI: 10.1016/j.enpol.2015.07.01

5. Valuing the manufacturing externalities of wind energy: Assessing the environmental profit and loss of wind turbines in Northern Europe. / Sovacool, Benjamin; Perea, Mario Alberto Munoz ; Matamoros, Alfredo Villa; Enevoldsen, Peter. / Wind Energy, Vol. 19, Nr. 9, 02.11.2015, s. 1623–1647. DOI: 10.1002/we.1941

6. Collaborate, Involve, or Defend? A Critical Stakeholder Assessment and Strategy for the Danish Hydrogen Electrolysis Industry. / Enevoldsen, Peter; Sovacool, Benjamin; Tambo, Torben. /International Journal of Hydrogen Energy, Vol. 39, Nr. 36, 12.12.2014, s. 20879–20887. / DOI: 10.1016/j.ijhydene.2014.10

7. Optimizing Investments in Coupled Offshore Wind -Electrolytic Hydrogen Storage Systems in Denmark. / Hou, Peng; Enevoldsen, Peter; Eichman, Joshua; Hu, Weihao; Jacobson, Mark; Chen, Zhe. Journal of Power Sources. 2017

Published Journal Articles - Danish Bibliometric Research Indicator 1

8. Do onshore and offshore wind farm development patterns differ? / Enevoldsen, Peter; Scott, Victor Valentine. / Energy for Sustainable Development, Vol. 35, Nr. December 2016, 2016, s. 41-51. / DOI: 10.1016/j.esd.2016.10.002

9. Integrating power systems for remote island energy supply: Lessons from Mykines, Faroe Islands. / Enevoldsen, Peter; Sovacool, Benjamin. I: Renewable Energy, Vol. 85, 2016, s. 642–648 / DOI: 10.1016/j.renene.2015.06.0

10. Addressing the Challenge of Determining Wind Conditions in Forests Dominated by Coniferous Trees. / Enevoldsen, Peter. / North American Clean Energy , Vol. 10, No. 4, 2016.

11. 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for 139 Countries of the World. / Jacobson, Mark Z. ; Delucchi, Mark A.; Bauer, Zack A.F.; Goodman, Savannah C.; Chapman, William E.; Cameron, Mary A.; Bozonnat, Cedric; Chobadi, Liat; Clonts, Hailey A.; Enevoldsen, Peter; Erwin, Jenny R.; Fobi, Simone N.; Goldstrom, Owen K.; Harrison, Sophie H.; Hennessy, Nora M.; Kwasnik, Ted M.; Liu, Jingyi; Lo, Jonathan; Meyer, Clayton B.; Morris, Sean B.; Moy, Kevin R.; O'Neill, Patrick L.; Petkov, Evan; Redfern, Stephanie; Schucker, Robin; Sontag, Mike A.; Wang, Jingfan; Weiner, Eric; Yachanin, Alex S. Joule. 2017

Submitted Journal Articles - Danish Bibliometric Research Indicator 2

1. Improving the Next Generation of Offshore Wind Energy Investments: Offshore Wind Farm Repowering Optimization. / Hou, Peng; Enevoldsen, Peter; Hu, Weihao; Chen, Zhe. Applied Energy. 2017

2. Perspectives on recent R&D efforts towards true redox flow batteries for load-shifting applications. /Kläning, Kristian; Enevoldsen, Peter. Energies. 2017

3. Constructing a Socio-Technical Framework on the Consequences of Deforestation and Wind Project Development: A Case Study of Northern Europe. Energy Policy. 2017

4. Critically assessing the innovation, cost, and performance dynamics of global wind energy development / Enevoldsen, Peter; Sovacool, Benjamin K.; Valentine, Scott Victor. Submitted to Energy & Environmental Science" / 2017

Submitted Journal Articles - Danish Bibliometric Research Indicator 1

5. Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden. / Enevoldsen, Peter; Permien, Finn. Renewable Energy. 2017

6. Estimating Wind Conditions in Forests using Roughness Lengths: A Matter of Data Input. / Enevoldsen, Peter. Wind Engineering. 2017

7. From lidar scans to roughness maps for wind resource modeling in forested areas. / Enevoldsen, Peter.; Dellwik, Ebba; Arnqvist, Johan; Floors, Rogier; Davis, Neil. / Wind Energy Science. 2017

Published Conference Papers

1. A Uniform Approach for Wind Simulations in Forested Areas: Examining the Importance of Data Inputs. / Enevoldsen, Peter. 2017. Abstract from WindEurope Resource Assessment 2017.

2. Aerial LIDAR scans for validation of CFD models in complex forested terrain. / Dellwik, Ebba; Arnqvist, F Johan; Cavar, Dalibor; Enevoldsen, Peter; van der Laan, Paul. 2016. Abstract from WindEurope, Hamburg, Germany.

3. Operational Optimization of Wind Energy Based Hydrogen Electrolysis Storage System Considering Electricity Market's Influence. / Hou, Peng; Enevoldsen, Peter; Hu, Weihao ; Chen, Zhe. 2016. Abstract from IEEE PES Asia-Pacific Power and Energy Engineering Conference

4. Onshore wind energy in forested areas in Northern Europe: Reviewing the risk. / Enevoldsen, Peter. / Journal of Cleaner Production, 2015.

5. Modeling the Social Acceptance of Wind Energy. / Enevoldsen, Peter; Sovacool, Benjamin. 2015. Paper presented at Energy Transitions 2015, Joensuu, Finland.

6. Towards a framework for evaluation of renewable energy storage projects: A study case of hydrogen and fuel cells in Denmark. / Tambo, Torben; Enevoldsen, Peter. Proceedings of the 24th International Association of Management of Technology Conference. Vol. 24 Cape Town, 2015.

7. Designing Business and Technology Management Work-Packages in Cleantech Research Projects. / Tambo, Torben; Enevoldsen, Peter. Proceedings of the 23rd International Association for Management of Technology Conference. red. / Yassir Hosni. Washington DC, USA : International Association for Management of Technology (IAMOT), 2014. s. 1-11.

8. Ivanell, Stefan; Arnqvist, Johan; Witha, Björn; Avila, Matias; Cavar, Dalibor; Chavez Arroyo, Roberto A.; Dellwik, Ebba; Enevoldsen, Peter; Espinosa, Hugo Olivares; Peralta, Carlos. / A forested site modelled with different microscale model approaches. / Abstract from Wind Energy Science Conference 2017.

Published Conference Posters

1. Wind Power in Forested Areas: Determining the Roughness Length and Displacement Height for Coniferous Trees. / Enevoldsen, Peter. 2016. Poster session presented at AWEA, New Orleans, USA.

Other Published Materials

1. Survey of stakeholders and responsibilities in the electricity market: Part 6.1 of work package 6 in the Power-2-Electrolysers project. / Enevoldsen, Peter; Tambo, Torben. 2015

6.2 Co-Author Statements

The following section introduces the co-author statements for the six journal articles presented in this dissertation.

6.2.1 Do onshore and offshore wind farm development patterns differ? / Enevoldsen, Peter; Valentine, Scott Victor.

AARHUS BSS | SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship

Full name of the Applicant: Peter Enevoldsen

This declaration concerns the following article/manuscript:

Title:	Do onshore and offshore wind farm development patterns differ?
Authors:	Peter Enevoldsen; Scott Victor Valentine

The article/manuscript is: Published

If published, state full reference: Do onshore and offshore wind farm development patterns differ? / Enevoldsen, Peter; Scott, Victor Valentine. I: Energy for Sustainable Development, Vol. 35, December 2016, 2016, s. 41-51.

Peter Enevoldsen 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	A
4. Interpretation of the results	C
5. Writing of the first draft of the manuscript	B
6. Finalization of the manuscript and submission	B

Signatures of the co-authors

Date	Name	Signature
15 Mar 2017	Scott Victor Valentine (scott.valentine@nus.edu.sg)	Digitally signed

Date:
Enevoldsen Peter
2017.07.24 14:22:11 +02'00'

Peter Enevoldsen

6.2.2 Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France. / Enevoldsen, Peter; Sovacool, Benjamin.

AARHUS BSS | SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship*

Full name of the PhD student: Peter Enevoldsen

This declaration concerns the following article/manuscript:

Title:	Examining the social acceptance of wind energy: Practical guidelines for onshore wind project development in France
Authors:	Peter Enevoldsen; Benjamin K. Sovacool

The article/manuscript is: Published x ☐

If published, state full reference: Examining the Social Acceptance of Wind Energy: Practical Guidelines for Onshore Wind Project Development in France. / Enevoldsen, Peter; Sovacool, Benjamin. I: Renewable & Sustainable Energy Reviews, Vol. 53, 01.2016, s. 178-184. / DOI: 10.1016/j.rser.2015.08.041

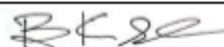Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No X

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	C
3. Involvement in the experimental work/clinical studies/data collection	A
4. Interpretation of the results	C
5. Writing of the first draft of the manuscript	B
6. Finalization of the manuscript and submission	B

Signatures of the co-authors

Date	Name	Signature
24/7-17	Benjamin K. Sovacool	*RKso*

Date: 24/7-17

Signature of the PhD student

6.2.3 Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden. /Enevoldsen, Peter; Perminen, Finn.

AARHUS BSS | SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship

Full name of the Applicant: Peter Enevoldsen

This declaration concerns the following article/manuscript:

Title:	Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden.
Authors:	Peter Enevoldsen; Finn Permien

The article/manuscript is: Published

If published, state full reference: Promoting Wind Power in Forested Areas: A Socio-Technical Wind Atlas for Sweden. /Enevoldsen, Peter; Permien, Finn. 2017. / Submitted to Renewable Energy Focus

Peter Enevoldsen 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	C
3. Involvement in the experimental work/clinical studies/data collection	C
4. Interpretation of the results	C
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
	Permien Finn-Hendrik	Digitally signed by Permien Finn-Hendrik DN: serialNumber=ZOOIKEWM, givenName=Finn-Hendrik, sn=Permien, o=Siemens, cn=Permien Finn-Hendrik Date: 2017.07.10 08:29:09 +02'00'	

Date:
Enevoldsen Peter
2017.07.24 14:07:14 +02'00'

Peter Enevoldsen

Declaration of co-authorship*

Full name of the PhD student: Peter Enevoldsen

This declaration concerns the following article/manuscript:

Title:	From Lidar scans to roughness maps for wind resource modeling in forested areas
Authors:	Ebba Dellwik; Rogier Floors; Neil Davis; Johan Arnqvist

The article/manuscript is: In preparation

Has the article/manuscript previously been used in other PhD or doctoral dissertations?
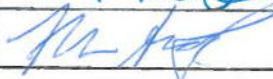
No

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	C
3. Involvement in the experimental work/clinical studies/data collection	B
4. Interpretation of the results	C
5. Writing of the first draft of the manuscript	B
6. Finalization of the manuscript and submission	E

Signatures of the co-authors

Date	Name	Signature
17/8 2017	EBBA DELLWIK	*(signed)*
25/8-2017	Rogier Ralph Floors	*(signed)*
17/8/17	Neil Davis	*(signed)*
18/8 2017	Johan Arnqvist	*(signed)*

In case of further co-authors please attach appendix

Date: 25/8/2017

(signature)

Signature of the PhD student

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