The geopolitical implications of renewables: Evidence from the increasing share of wind energy in the Danish electricity system

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The geopolitics of the energy transition

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Preface

Dear reader,

In front of you lies the final version of my thesis in fulfillment for the Master program Complex Systems Engineering and Management at the Technical University in Delft. When I started this journey in February, no one had ever heard of the one and a half meter society and face masks were barely seen. Sadly, we all know it now. It has been a journey of six months that took an unexpected direction. A new direction inducing advantages but many disadvantages too. Working from home without seeing many people was not always easy. It has however been a great pleasure to contribute to this newly arising study field. Especially because I could do it with the help of many others. I would therefore like to thank a few people.

I would first like to thanks all the interviewees that helped me by answering questions and providing me with interesting ideas and knowledge. Without you I wouldn't have been able to do it.

I would also like to thank the members of my graduation committee, Rolf, Daniel and Rob for their time and constructive feedback. Special credits go to my first supervisor Daniel. Great thanks for your input and the discussions that we had during our Skype sessions. I really enjoyed working with you on this relatively new issue and I admire your knowledge and experience on the topic.

I would further like thank my Accenture supervisors Alex and Laura. When I started my internship in February we couldn't have imagined that it would end like this. It was a pity that I could not see more of Accenture and meet you guys more often in real life. Nevertheless, I really enjoyed working with both of you. You were involved until the very last moment, always happy to answer questions or provide me with feedback. You not only helped me to improve my thesis but also to strengthen my professional working skills.

I also want to thank my family and friends for all their love, support and much needed distraction during the weekends. Lastly I want to thank my boyfriend Joris. Your daily cups of coffee, help and great trust were of significant importance.

The global transition towards renewable energy as described in my thesis is an indispensable development, no matter what challenges we will face. The findings of this study hopefully form not only a suitable (and practically applicable) conclusion of my studies in Delft, but also a substantial contribution to that global transition.

Simone Borggreve

Amsterdam, September 2020

Executive summary

The technical and geographical characteristics of fossil fuels have shaped interstate energy relations for decades. The ongoing energy transition increases the share of renewables in the electricity mix. Since technical and geographical characteristics of renewables differ significantly from those of fossil fuels, renewables are assumed to affect interstate energy relations in a different way. It is yet unknown how these deviating characteristics will exactly shape international energy relations. While literature on the new issue of geopolitics of renewables is slowly expanding, evidence from concrete cases is still missing. Moreover, most of the existing literature groups renewables together and does not consider the specific impact that different types of renewables might have. This study focuses on filling these literature gaps by examining the geopolitical implications of large-scale wind power in the Danish electricity system. Wind power is assumed to be a substantial part of the future energy mix and it is therefore important to understand how the specific characteristics of wind energy can impact interstate energy relations. Denmark is selected as case for this study since the country has developed into a frontrunner on the deployment of wind energy. In 2019, wind power accounted for 47 percent of Denmark's total electricity usage.

The main research question that this study aims to answer is as follows.

"What are the geopolitical implications of a significant increase of wind energy in the Danish electricity system?"

The goal of this research is to collect evidence on the geopolitical implications of the energy transition by focussing on a concrete case study; wind power in the Danish electricity system. More specifically, this study aims to examine how interstate energy relations of Denmark have shifted between 1990 and 2018 and to assess to what extent these shifts can be attributed to the technical and geographical characteristics of wind energy.

In order to answer the main research question, this study constructs a framework of analysis that enables outlining of geopolitical implications of wind energy. The framework consists of four different steps. First, the technical and geographical characteristics of the energy system are outlined. The second step examines how renewables reshape the economic characteristics of energy markets. The third step investigates the energy security of a country, the policy responses accessible to react on the energy security situation and the shifting patterns of cooperation or conflict. The last step links the prior steps to each other and reflects on the relationship between the technical and geographical characteristics and the shifting interstate energy relations. The selected variables of the framework are specified to the characteristics of wind power. Both quantitative and qualitative indicators are used to measure the variables. Whereas the quantitative indicators outline the characteristics of the system, the qualitative indicators evaluate and interpret the findings. Desk research and interviews with 17 experts from the field are used to obtain the data. The framework is consecutively applied to the Danish electricity system in 1990 and 2018, in order to draft two 'portraits' of the electricity system for both years.

This research finds seven differences in Danish interstate energy relations between 1990 and 2018.

- **Increased production of domestic wind power decreases import dependency on foreign fossil fuels.** Denmark reduced its dependency on fossil fuels from foreign countries and became more self-sufficient.
- **Intensification of market-based electricity trade induces new interstate dependencies.** The Danish TSO has significantly increased cross-border interconnector capacity in order to deal with the fluctuating character of wind power. Denmark therefore depends on electricity imports from its neighbours in times of low wind speeds, but experts do not consider this dependency

problematic. On the contrary, interviewees describe how it contributes to a better integrated, more stable market.

- **Regionalization of energy relations.** Denmark used to import fossil fuels from all over the world, now its major trade partners are Northern European countries.
- **Denmark faces increasing political influence through knowledge sharing.** The transition has induced a shift in focus from control over resources to control over knowledge. Danish parties understand this very well. Through the export of knowledge on the energy sector, Denmark is gaining worldwide political influence, and the market share of Danish wind power companies is increasing.
- **Increased interstate cooperation on the supply chain of wind turbines.** Wind turbine companies realize that cooperation helps to optimize the supply chain, reduces costs and leads to higher product quality. More cooperation and dependencies are hence observed in the wind power supply chain, in which Northern European countries make use of each other's strengths and specializations.
- **Increased dependency on critical materials**. While the issue of critical materials is largely discussed in literature, Danish experts consider it as a concern, rather than as a serious problem. Countries and companies should be aware of the dependency on critical materials in order to find ways to reduce the dependency.
- **Increased threat for cross-border disagreement**. Since cross-border transmission lines gained importance over the last decades, the availability of capacity has become more important as well. Still, disagreements or tensions are extremely unlikely to lead to serious conflicts or wars between Denmark and its neighbours.

The second part of the results assessed to what extent the described changes can be attributed to the characteristics of wind power. This research shows that a mix of various factors have contributed to the shifting interstate energy relations. Most of the important factors are contextual developments. Still, the shifts in interstate energy relations can to a small extent be attributed to the technical and geographical characteristics of wind power. Especially the intermittent nature of wind and the geographic location of Denmark, i.e. good wind conditions and located close to countries with stable hydropower sources, are important attributors to change. The technical system characteristics 'design of wind turbines' and 'network technology and topology' have influenced interstate energy relations as well. The most notable contextual factor that explains the shifts in energy relations is the possibility to generate revenues. Denmark and its trade partners understand that market integration (of the electricity market and the wind turbine sector) leads to more competition, creating a stable and more efficient market that enables countries to generate revenues. The possibility to earn money has thus increased international cooperation and competition. Policy, climate concerns, a well-functioning trade market (Nord Pool) and good relations with neighbouring countries are factors that also influence the energy relations and dependencies of Denmark.

Thus, what are the geopolitical implications of a significant increase of wind energy in the Danish electricity system? These come down to three major points. Denmark is increasingly trading electricity with neighbouring countries. It even depends on these countries to deal with the fluctuating nature of wind power. The increased electricity trade has led to a better integrated Northern European electricity market, in which some contested dependencies are replaced by valuable interstate cooperation. The new system allows for generation of revenues and it stabilizes the market. Second, being first mover in the wind turbine sector has strengthened the position of Danish wind power companies. It has increased Danish export of components related to the energy sector, which in turn created job opportunities and generates income. Last, Denmark uses the electricity sector to gain global influence. While Denmark is a small country, it is punching above its weight in terms of energy policy.

The far-reaching Danish knowledge and experience is opening doors to foreign countries. New partnerships do not only increase political influence, they also help to increase global market share of Danish companies.

The novelty of the field leaves great space for future research which should mostly focus on providing evidence from real-life case studies. Future research should for example focus on the geopolitical implications of other types of renewables than wind power. The constructed framework should be applied to wind power systems in other countries. Future studies should also focus on the geopolitical implications of the decreasing demand of fossil fuels. Last, studies into the conceptualization of the main variables is needed.

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1. Introduction

1.1 Problem context

1.1.1 Background

The Desertec Industrial Initiative (DII) launched a renewable energy project plan in 2009. The aim of the project was twofold: to generate large amounts of renewable power in the Middle East and North Africa (MENA) region for the local population, and to supply Europe by large-scale export of renewable energy, covering 15% of Europe's power needs in 2050 (Miltenburg, 2014). The enormous production potential of the desert was hoped to bring economic wealth to the region and supply Europe from cheap and clean energy. Yet, large-scale electricity imports raised questions in Europe about the security of European electricity supply. Experts from the field expressed concern about the political reliability of the trade partners, energy security, the increasing energy import dependency and the possibility for exporting countries to use electricity as 'energy weapon' (Lilliestam & Ellenbeck, 2011). The project was also criticised because of its postcolonial character in which European countries would benefit more from asymmetrical dependencies. Despite the great potential of the project, parties failed to turn theory into practice. Most of the stakeholders have now abandoned DII.

This example demonstrates that the energy transition is more than just a change in technology, it is influenced by political processes as well. The example illustrates that integration of renewables can lead to newly arising interstate energy relations and dependencies that must be well considered by all the involved parties. The new energy system structures induced by an increasing share of renewables, leave national governments with new challenges concerning energy security, policy strategies and patterns of cooperation and conflict. The example shows that the project – notwithstanding the superior weather conditions in the MENA region - forced Europe to consider a variety of questions: do we want to import cheap electricity and depend on our Southern neighbours for electricity supply? Or, do we prefer to secure domestic electricity production? And if we strive to import parts of our consumption, to what extent can we trust our new trade partners? The MENA region, in turn, had to decide whether it wanted to depend on Europe for a significant part of its income, and whether it wanted to export part of the generated electricity rather than using it for own consumption. Considerations of strategic realities of the-end-state finally led to a termination of the project.

The crucial role that energy plays in economies forces national governments to consider these new strategic realities. Energy contributes to economic growth and is crucial to guarantee stability in a country (Grivach et al., 2017). Nations therefore position themselves in a way that they can safeguard energy security (Criekemans, 2011). For decades, this position and the resulting interstate relations have been largely determined by the geographical and technical characteristics of fossil fuels (Scholten, 2018). Increasing penetration of renewables does affect relations between countries, as the DII project illustrates (IRENA, 2019). Characteristics from renewables differ from those of fossil fuels. Renewables are abundant and intermittent. Generation technologies of renewable energy sources lend themselves to decentral generation and the electric nature of electricity limits long-distance transportation due to high losses. Fossil fuels, on the other hand, are finite and geographically bounded. Electricity is mostly generated in large-scale centralized power plants. The solid, liquid and gaseous nature allow fossil fuels to be transported in various ways, e.g. through pipelines, overseas, in trucks over roads or over rails, and they allow for long-distance transportation without high energy-losses (Scholten, 2018). It is yet unclear how the deviating characteristics of renewables are going to affect geopolitics and interstate energy relations.

1.1.2 Problem description

The technical and geographical characteristics of fossil fuels have thus shaped interstate energy trade relations for decades (Scholten, 2018). The ongoing energy transition and increasing amount of renewable energy sources (RES) is significantly changing the energy system. Renewables are not merely altering the energy mix, they induce a much deeper transformation of the entire system. The deviating technical and geographical characteristics cause shifts in the technical, economic and social structure of renewable energy systems. These new structures also affect geopolitics (IRENA, 2019; O'Sullivan et al., 2017; Scholten, 2018; Vakulchuk et al., 2020). [1] The example in the previous section illustrates how the willingness to become greener forces nations or regions to come up with new energy strategies, in which policy aims and available policy means must be reconsidered. These strategies might induce shifts in interstate energy relations and activate new patterns of cooperation or conflict between countries.

The number of researchers drawing attention to geopolitical issues is slowly yet gradually increasing. While it remains largely uncertain how renewables will exactly affect geopolitics, most researchers seem to agree on the fact that renewable energy systems will solve some of the old geopolitical challenges, but will induce new, similar challenges itself (Ang et al., 2015; Johansson, 2013a; O'Sullivan et al., 2017; Rothkopf, 2009; Scholten, 2018). Ang et al. (2015) for example, highlight the issue that renewables might decrease the need for energy imports but that they are plagued with problems of intermittency. Fossil fuel imports decrease but higher grid interconnection is necessary to deal with peaks in supply, creating a new type of interdependency. Another difficulty is that the production of renewable energy technologies requires serious amounts of scarce resources (Scholten & Bosman, 2016). Dependence on fossil fuels might therefore be replaced by dependence on these scarce resources (Hache, 2018).

These newly arising challenges and the shifting energy dependencies leave national governments with important questions. The crucial role that energy plays in terms of economic prosperity and national security, makes it highly important for governments to understand how the transition might impact their position in the international arena. They have to determine what kind of new, strategic role they want to play in these shifting relations. This also induces the question what an appropriate strategy looks like. Will countries produce renewable energy themselves or will they import it from countries with more beneficial conditions that can produce cheaper energy? How do countries guarantee security of supply? What kind of new interstate dependencies arise? If states want to reap the benefits and overcome the challenges of the energy transition, it is crucial to understand how the increasing share of RES influences geopolitical issues such as energy security, policy considerations of producer, consumer and transit-countries, and interstate energy trade relations. By asking the right questions and timely identifying threats, countries can contribute to a peaceful and efficient transition (Goldthau et al., 2019). Not only governments, but also businesses and policies of other nations shape the geopolitical role of a country (Ole & Austvik, 2018). As Pascual (2015) describes, to understand the geopolitics of energy, governments must understand how changing energy markets and market players affect nations and not just how nations can intervene in energy markets. This study hence tries to understand how the geopolitical position of a country is shaped by renewables and which role governments and businesses have in this position. Research on this topic has been limited thus far, as the next section demonstrates.

[1] The used definition of the concept geopolitics is given in section 2.1.

1.1.3 Knowledge gaps

The emerging area of geopolitics of renewable energy raises many questions. The novelty of the field is evident in the existing literature, as many uncertainties still exist. The identified knowledge gaps connected to this thesis are as follows.

- There is a need for more concrete case studies on the geopolitical implications of renewables (Scholten & Bosman, 2016; Vakulchuk et al., 2020).
- There is a lack of knowledge on the geopolitical consequences of the different types of renewables (Scholten & Bosman, 2018) . Most of the authors in this emerging field, such as IRENA (2019), Hache (2018), O'Sullivan et al. (2017), Overland (2019) and Gökgöz & Güvercin (2018) group RES together in their geopolitical analysis. The specific impact related to different types of RES such as wind power, solar power, biofuels and hydropower has barely been studied.
- Much of the existing frameworks and analytical tools to study geopolitical implications of energy stem from the fossil fuel era. The lack of frameworks specified to the characteristics of renewables provided little knowledge on geopolitical implications of renewables (Scholten, 2018; Vakulchuk et al., 2020). An update of these tools is needed, in order to contribute to theory development in the long run.
- Governments are facing new challenges. They must position themselves in a shifting international playing field. To do so, deeper understanding of the geopolitical consequences of renewable energy sources is required.

1.1.4 Problem statement

This study derives the following problem statement from the problem description and knowledge gaps above:

It is unclear how different types of renewable energy sources affect geopolitics in concrete cases in terms of energy security issues, policy considerations and patterns of cooperation and conflict.

The addition 'concrete cases' in the meaning of tangible case studies is important here, as this was defined a substantial knowledge gap in the section above. This study therefore investigates the geopolitical implications of the increasing share of wind energy in Denmark. The following section introduces the Danish electricity system and describes its relevance for this study.

1.2 Case introduction: wind energy in the Danish electricity system

Wind energy in the Danish electricity system is selected as case for this research.[2] This section presents the relevance of this case in the emerging research area of geopolitics of renewables. It furthermore presents the scope of the study and describes the included and excluded elements of the system.

The installed global wind capacity is growing. Like solar energy, wind power has faced huge costs reductions and has grown rapidly over the last decade (IRENA, 2019). It is assumed to be a substantial part of the future energy mix and it is hence important to understand how the specific characteristics of wind energy can impact interstate energy relations (Vakulckuk et al., 2020; Wiser et al., 2011). Wind energy is therefore selected as specific type of renewable energy source. Denmark is chosen as country to study the impacts of wind power. Denmark has developed into a frontrunner on the deployment of wind energy (Sovacool & Tambo, 2016). In 2019, 16 terawatt hours of electricity was produced by wind turbines in the country, meaning that wind energy accounted for 47 percent of

[2] The scope is intentionally limited to the electricity sector. Wind power produces electricity and it is therefore assumed that wind power mostly impacts the electricity sector. The whole energy sector is actually changing because of the energy transition, but since the aim of this study is to outline the implications specifically induced by increasing the share of wind, these other changes are not included in this research.

Denmark's total electricity usage in 2019 (Petrova, 2020).[3] The country is therewith far in front of rival countries, such as Ireland, Portugal and Germany with respectively 33, 27 and 26 percent of wind energy in their electricity mix (Sesto & Lipman, 2020). Denmark's forefront position makes Denmark the most appropriate country to study the geopolitical implications of wind energy as implications are likely to be most evident there. The geopolitical analysis includes examination of system characteristics of source, generation and transmission in Denmark.[4,5] These system characteristics are assessed in the years 1990 and 2018. 1990 is selected as 'reference year', that is used to compare how interstate energy relations have changed over a period of time. Wind power generation was still limited in 1990, i.e. it contributed for less than 3 percent to the total electricity mix (Danish Energy Agency, 2020). Moreover, the year 1990 is seen as tipping point in the Danish energy policy, since the focus shifted to green energy from then on (Rüdiger, 2019b). The year 2018 is selected to study the newly evolved energy relations, simply because essential information is not yet available for 2019 and 2020. The focus of the year 2018 is on wind power in particular, relations induced by other renewables such as solar power or biomass are not included in this study.

It is important to note that a clear distinction of the closely interrelated fossil fuel and renewable energy systems is difficult. The energy sector is currently in transition, fossil fuels are still dominating the system. Hence, the geopolitics of traditional and renewable energy will coexist for quite some time to come (Paltsev, 2016). Fossil fuels are, and will be, influencing the geopolitical position of Denmark for the upcoming decades (Criekemans, 2018). Although it might be difficult to clearly distinguish the impact of both, this research attempts to merely focus on the geopolitical consequences induced by wind power. Thus, the key focus of this study is on the newly arising interstate energy relations and dependencies caused by the increasing share of wind energy in the system rather than the implications of decreasing fossil fuels.[6]

Another observation concerns the different phases of the transition towards a renewable energy system. Each phase comes with new challenges and includes different (technical) system characteristics. For example, the technical adaptations that must be made to penetrate 50 percent of wind power significantly differ from the changes that must be made to penetrate 80 percent of wind energy. This study strives to outline the adaptations that have been made to integrate the first 47 percent of wind power. The focus of this study is therefore on the transitional phase rather than the post-transition phase when the system only consist of renewables. The literature section addresses the systemic changes in a more general way. It is outside the scope of this thesis to go into detail on highly technical aspects, since these technicalities are assumed to affect the system on a national, rather than an international level. This study thus aims to sketch a general profile of the systemic characteristics that might influence interstate energy relations.

1.3 Research questions and objective

1.3.1 Research objective

The goal of this research is to collect evidence on the geopolitical implications of the energy transition by focussing on a concrete case study; wind power in the Danish electricity system. More specifically, this study aims to examine how interstate energy relations of Denmark have shifted between

[3] Both onshore and offshore wind turbines add to this percentage of 47 percent. They are both included in this study.
[4] This distinction is obtained from Scholten's (2018) framework, which will be discussed in chapter 2.
[5] Electricity consumption is left out purposefully. Electricity produced by wind power is integrated into the electricity grid and mixed with grey electricity. It is therefore hardly possible to determine where green electricity produced from wind power is exactly going to, nor what the location of demand is.
[6] It is essential to also examine how relations change because of a decreasing demand for fossil fuels. This, however, involves an entire new study area and is not therefore included in this research.

1990 and 2018 and to assess to what extent these shifts can be attributed to the technical and geographical characteristics of wind energy.

1.3.2 Research questions

This study strives to answer the following research question:

"What are the geopolitical implications of a significant increase of wind energy in the Danish electricity system?"

The research question is divided into four separate sub-questions:

1. **How to assess the geopolitical implications of an increasing share of wind energy in national energy systems?**
2. **What were the features of the Danish electricity system and interstate energy relations in 1990 and 2018?**
3. **What are the main differences and similarities between 1990 and 2018 and can they all be attributed to the technical and geographical characteristics of wind energy systems?**
4. **What are the practical and strategic implications for wind energy integration in countries' electricity systems?**

Answering these four sub-questions contributes to formulate a comprehensive answer of the main research question. The exact data and research methods used to answer these four sub-questions are further described in section 1.4.3.

1.3.3 Practical and theoretical relevance

This study assesses the geopolitical impact of the increasing share of wind energy in the Danish electricity system. The relevance for observing this impact is both practical and theoretical. In a practical sense it is useful for the Danish government to get insight into the new interstate energy relations and dependencies that arise because of the penetration of wind energy. Since these relations are assumed to influence Denmark's political position, is is important for the Danish government to be aware of them. The study can highlight new challenges or vulnerabilities that should be considered when the share of wind is further increased, or it can highlight opportunities that can be further exploited. Practical and strategical implications are therefore formulated in chapter 5. More importantly, the findings of this study are relevant for governments of other countries that aim to increase the share of wind energy in their energy mix as well. Especially countries with similar characteristics as Denmark can use the outcomes in their energy strategies. Understanding the systemic and geopolitical consequences is thus assumed to be beneficial for Denmark itself, as well as for other countries. Last, the findings are useful to evaluate the role of the European Union in the Danish energy transition. The case of Denmark can demonstrate what countries need from the EU for a successful transition. Concrete policy recommendations for Denmark, other countries and for the EU are hence made at the end of this study.

The study is theoretically relevant in several ways. First, since the energy transition is still in its early phase, not much research on the geopolitics of renewables is based on concrete cases. Most of the literature relies on anecdotal evidence, but concrete case studies are missing (Vakulchuk et al., 2020). This study thus adds by focussing on the concrete case of wind energy in Denmark. It therewith contributes to the process of gathering knowledge on which new theories can be built in the future. Second, the emerging field of geopolitics of renewables has thus far been grouping RES together in their geopolitical analysis. By focussing on the geopolitical implications of a specific type of renewable, e.g. wind energy, this research deepens understanding of the problem. Conducting a large number of these specific case studies might contribute to theory construction in the future. Third, the relatively new framework, as developed by Scholten (2018) is used in this research. Application of the framework is not only beneficial to generate knowledge on geopolitics of wind energy, it also identifies strengths and weaknesses of the framework itself. Recommendations to further improve the framework will follow at the end of this study, contributing to the construction of tools and frameworks that can be used to map the geopolitical implications of renewables.

1.4 Research approach

This section provides the research approach of the study. The research design is presented first. The selected framework is introduced thereafter and data requirements and research methods to answer each sub-question are discussed last.

1.4.1 Research design

The structure of the report is schematically presented in Figure 1. First, the problem is introduced and the main research question and objectives are formulated. Consequently, a literature review is provided in which the term geopolitics is defined and literature on both geopolitics of fossil fuels and renewables is discussed. Then, the framework used to assess the geopolitical implications of RES is introduced. The framework is adapted to the specific characteristics of wind power. The concepts are operationalised at the end of chapter 2. Chapter 3 applies the framework to the electricity system in Denmark in 1990 and in 2018. This chapter presents the geographical, technical and economic aspects as well as the energy interstate relations. The latter, interstate energy relations, entails an energy security analysis, policy analysis and investigation of energy related trade patterns of cooperation or conflict. The third chapter is rather descriptive by nature, trying to factually describe two different situations. Chapter 4 includes the analytical part of the study. This chapter compares the results of the interstate energy relations in both years. Conclusions are drawn on the differences and similarities between them. More importantly, this chapter tries to assess to what extent the differences and similarities can be declared by the geographic and technical characteristics of wind power or whether they must be attributed to other, contextual developments. Following these findings, the research sets out practical and strategic implications for the Danish government. Finally, the drawbacks of the research are discussed, and the main research question is answered.

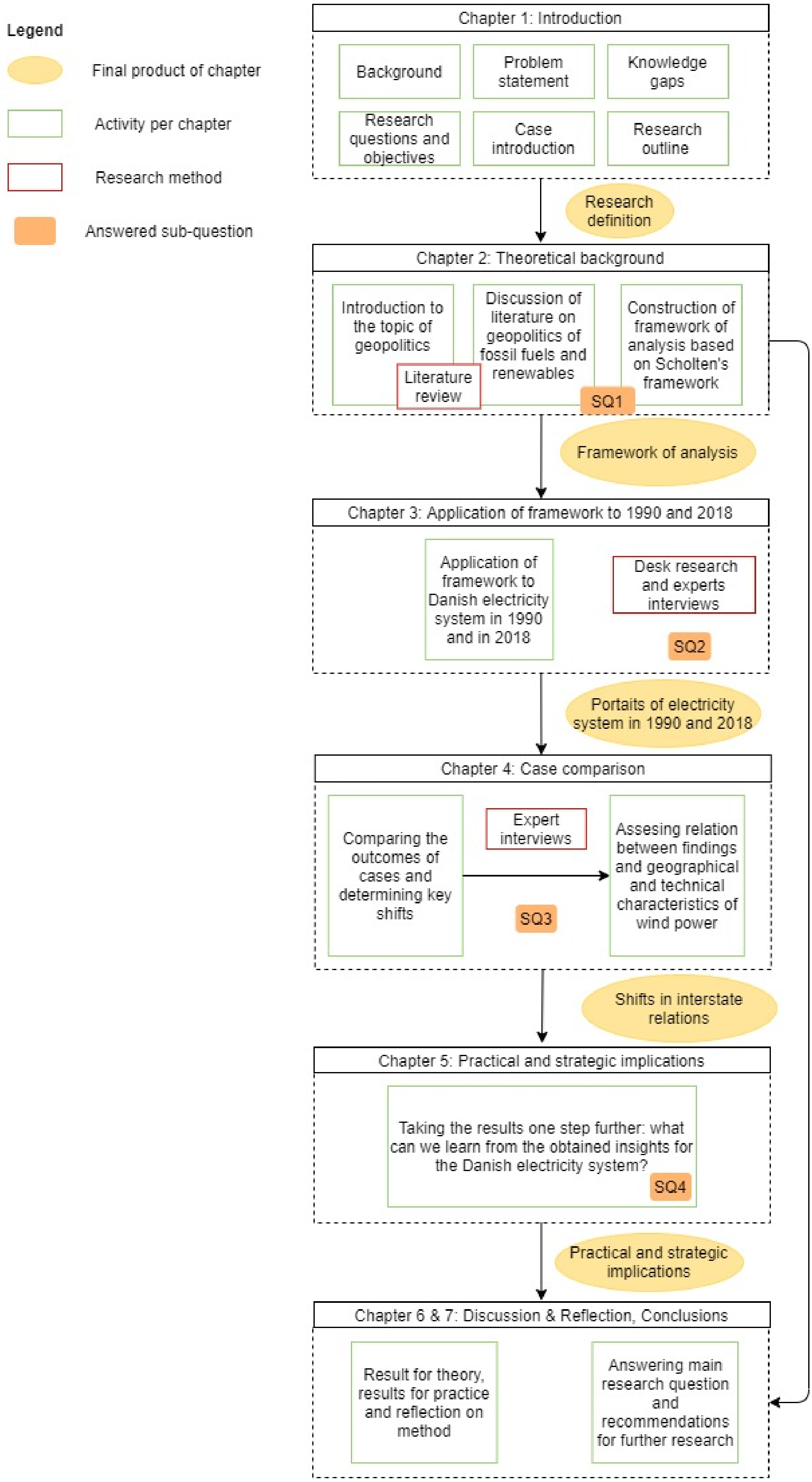

Figure 1. Research design

1.4.2 Selected framework

Most of the existing frameworks and theories on the geopolitics of energy stem from the field of International Relations (IR) or energy security (Bradshaw, 2009; Dannreuther, 2010; Grivach et al., 2017; Mohapatra, 2017; Ole & Austvik, 2018). These frameworks and theories are mostly based on the geographically concentrated and scarce nature of fossil fuels. Dannreuther (2010) illustrates for example how international energy politics can be approached from two of the key theories of IR: realism and liberalism. Realism puts emphasis on the concept of energy security, which can be defined as unlimited access to, and control over energy sources (Siddi, 2017). Having this control or access is a key ingredient to power, making states compete for it. Conflicts or wars over these sources are therefore highly likely (Dannreuther, 2010). Conversely, liberalism argues that interdependence and cooperation between states is important and beneficial for countries. Energy producers can make profits by selling surplus production and energy consumers want to have peaceful, commercial access to energy resource (Siddi, 2017). The geographically concentrated character plays a crucial role in how both IR theories approach the energy field and in the expected geopolitical impact.

Characteristics of renewable energy sources differ considerably from those of fossil fuels. Most renewables are not geographically concentrated, and every country has access to at least some form of renewable energy (Scholten & Bosman, 2016). Furthermore, the spatial characteristics of the total supply chain of renewable energy systems differ (Pieterse, 2008). Infrastructure technologies such as physical network assets and control facilities that are necessary to bring renewables to the market change significantly (Scholten & Bosman, 2016). Due to these deviating characteristics of renewables and their supply chain, it is hardly possible to apply existing frameworks or concepts from geopolitics of conventional energy (O'Sullivan et al., 2017). Better understanding of the systemic changes, e.g. technical or economic changes, induced by renewables and their effect on interstate energy relations is required first. After improved understanding of these deviating system elements, relevant insights from the large amount of literature on geopolitics, IR and energy security could further add to the debate of geopolitics of renewables.

Thus, a new framework that enables to examine the different characteristics of renewables, is indispensable to understand their geopolitical implications. Changed system characteristics must systematically outlined first before diving deeper into the potential geopolitical implications. The field of renewables and geopolitics is still new and existing studies only offer a fragmented insight (Scholten, 2018). Pieterse (2008) for example made a first attempt to construct a conceptual framework, but failed to schematically distinguish different concepts. Scholten (2018) has set up a common framework that enables scholars to assess the geopolitical implications of renewables. His framework aims to break down the complex issue of geopolitics of renewables into controllable pieces that help to structure the debate on the topic. It aims to provide insight into the relation between renewables and geopolitics, including the supply chain of renewables.

This study uses the framework of Scholten (2018) since it is the first, and most practical attempt to schematically outline geopolitical implications of renewable energy systems. No other frameworks thus far allow for such a thorough analysis of the system characteristics and their geopolitical impacts. Still, the framework is developed to approach the topic from a global, systemic view rather than to concentrate on concrete case studies. The focus is on renewables in general and not on specific forms of renewables. This study therefore adapted the existing framework, and modified it to the specific characteristics of wind power in Denmark.[7] Literature review is used to identify variables that are relevant for electricity systems based on wind power. A new framework based on the one of Scholten (2018) is thus constructed to assess geopolitical implications of wind power in Denmark. It is important

[7] The framework is constructed in section 2.2.

to note that the created framework is used as conceptual rather than theoretical framework. I.e. the framework helps to distinguish and structure the different concepts and variables, rather than that it scientifically declares the relations between them.

Not only the decision making process that selects the framework – as discussed above – but also the decision making process that includes or omits certain variables, largely determines what is measured within a study (Ang et al., 2015b). Since what is analysed fundamentally influences the final outcomes, variable selection is another important pillar of this research. Gasser (2020) notes a considerable lack of transparency in the selection procedures of relevant variables among a wide range of studies. Considering the significant impact of the indicators, insufficient transparency can affect the results, and the validity of the study. Hence, to safeguard transparency and make the reader aware of the inevitable biases of the author, all taken steps and decisions are outlined in this study. The framework construction process consists of several steps, that are based on the framework construction method as created by Gasser (2020), which boils down to:

1. Development of framework that explains the phenomenon's to be measured
2. One-by-one assessment of Scholten's (2018) variables and providing rationale for leaving out or altering certain variables
3. Elaboration of additionally selected variables and providing rationale for why these variables are added

Step 1 is covered in section 2.1, which elaborates on the general concept of geopolitics, geopolitics of fossil fuels and geopolitics of renewables. Step 2 and 3 are elaborated upon in section 2.2. The overall research methods used to answer each sub-question are discussed first.

1.4.3 Research methods

This section substantiates the used research methods for each sub-question, the required data, and the potential limitations of the used approach for each of the sub-questions. A summary of the section is presented in Table 3. The table shortly presents limitations of the research method, which are further discussed at the end of this study, in section 5.3.1.

Theoretical background (sub-question 1)

The aim of the first sub-question is two-fold: to provide the reader with a firm foundation of background knowledge on the topic, and to construct a framework through which the geopolitical implications of wind power can be assessed.

The first section is divided into three parts. The concept of geopolitics is shortly defined first, followed by a discussion of the geopolitics of conventional energy sources and finally a discussion of literature on the geopolitics of renewables. Data collection for these literate reviews was done by searching for relevant scientific journal articles, available through Scopus or Google Scholar in the period 1990-2020. The used search string concerns "(energy security OR conflict OR cooperation) AND (renewable OR renewable energy OR wind power OR wind energy OR oil OR gas) AND (geopolitics)". Back-referencing of sources cited by the identified papers was used to find additional relevant papers. Two major selection criteria to exclude studies were used. Studies focussing on a particular country or region except for Denmark (e.g. energy security assessment studies) were excluded since the aim was to provide insight into the general expectations from the field rather than to outline evidence from existing cases. Second, studies on specific energy sources or carriers other than wind power (e.g. hydrogen or solar power) have neither been included since the focus is on geopolitical implications of wind energy in particular.

The second part of this chapter zooms in on the framework construction. As described in the previous section, Scholten's (2018) framework was applied in this research and the four steps distinguished in his framework were taken over. Yet, the concrete variables used to outline each step were adjusted to the specific case of wind power in a particular country. The variables as identified by Scholten were used as search term, in combination with "(wind power OR wind energy OR wind energy systems)", so for example "(critical materials) AND (wind power OR wind energy OR wind energy systems)".

Framework application (sub-question 2)

The constructed framework from chapter 2 is applied to the Danish electricity system in chapter 3. This chapter has a rather descriptive nature. The main aim is to objectively outline the characteristics of the electricity systems in 1990 and 2018, and to draw two 'portraits' of the situation in both years. The framework entails quantitative and qualitative indicators, which allow for outlining and evaluating the shifts in interstate energy relations. The quantitative analysis consist of the assessment of the quantitative indicators, such as the size of electricity flows or the size of interconnector capacity in megawatts. The qualitative indicators represent the variables with a qualitative-subjective nature, i.e. dependencies, energy strategies, patterns of conflict and cooperation. Whereas the quantitative indicators aim to outline *how* characteristics of both systems have shifted, the qualitative indicators try to explain *why* they did. The methods used to obtain the data are desk research and expert interviews.

Desk research

Data on the geographical, technical and economic characteristics of the electricity systems was mainly obtained from desk research. Various databases were used to extract information on the qualitative and quantitative indicators. Particularly databases from the Danish Energy Agency (DEA), International Energy Agency (IEA), the European Commission and BP were used to obtain the quantitative data. Additional reports from Energinet (the Danish Transmission System Operator), the DEA, policy documents of the Danish governments and IRENA provided information on the qualitative indicators. Academic papers analysing the history of Danish energy policy were used in addition, e.g. articles from Mogens Rüdiger, who did extensive research to energy policy in Denmark. These academic papers contributed to the understanding of the context in which the numbers developed.

Interviews

The mentioned quantitative and qualitative data illustrates and explains the impact of wind energy on the electricity system. Still, they insufficiently outline and evaluate the types of relations and dependencies between Denmark and other countries. To examine these interstate energy relations, an additional qualitative method of data collection was used. Experts from the electricity sector were interviewed to expose the true impact of wind on Denmark's international position. Expert interviews add to this research in two ways. First, interviews were used to collect data that could not be find via desk research. Again, as this is a relatively new topic, the data coverage is still lacking. The interviews were thus in the first place used to collect information that was difficult to obtain from online reports or databases. Second, experiences of the interviewees were assumed to be a valuable addition to the predominantly factual information obtained from desk research. Experts in the field have opinions, attitudes and experiences which are of paramount importance for a deeper understanding of the issue (Gill, Stewart, Treasure, & Chadwick, 2008). Experts can for example assess to what extent a founded dependency between Denmark and another country is considered problematic. Their knowledge and experience were hence used to enhance understanding on the topic and to assess the observed changes. Interviewing should be considered as a cyclical process in this study (Boeije & Bleijenbergh, 2019). The interviews were initially used to collect data. In later stages they were also used to verify newly identified relations based on insights from earlier interviews.

In total,17 stakeholders were interviewed. An overview of the interviewees can be found in Table 1 below. Some of the interviewees are not mentioned with name and function because of privacy reasons. To obtain a wide range of perspective, experts with different backgrounds were selected. Experts from research institutes, governmental organizations, energy generating companies and companies in the wind turbine sector were approached. From the 17 interviewees, 12 are working in the

Danish energy sector and five are working in the Dutch energy sector. These latter have been added to zoom out on the case and be able to put observations from Denmark into a broader perspective. Furthermore, these interviews added valuable insights on cooperation between countries in the Northern European region. Experts were mainly approached via LinkedIn and via the personal network of the researcher. Snowballing, a process of finding new interviewees by asking initial contacts to suggest potential interviewees was used to expand the network and reach more potential interviewees (Rowley, 2012). Most of the interviews were held via Skype and two via telephone. Due to the ongoing COVID-19 crisis it was unfortunately not possible to meet any of the interviewees in person. The interviews lasted between 20 minutes and five quarter hours, depending on the agenda of the participant.

The conducted interviews were semi-structured. That are interviews consisting of several questions that help to demarcate the research area and still leave space for the interviewer to diverge (Gill et al., 2008). They are informal in tone and allow for open questions of the interviewer and open responses by the interviewees (Longhurst, 2013). This type of interview was selected since a semi-structured interview allows for collecting of opinions, emotions and experiences in complex issues (Longhurst, 2013; Rowley, 2012). A list of interview questions is added in Appendix A. The list consists of 17 open questions. For almost all questions, a follow-up question was formulated in advance to assist the interviewer during the interview. Depending on the background of each interviewee, certain questions were left out in some interviews since these questions were formulated according to someone's background. For example, experts from the Dutch energy sector were not asked about Danish energy strategies or policies and expert working at wind turbine companies were asked some more questions on critical materials.

Table 1

List of interviewees

	Expert	**Date**	**Organization**	**Function**	**Sub-group**
1	Anonymous 1	25-06	-	-	Industry
2	Kenneth Hansen	25-06	Danish Energy Agency	Energy Advisor	Government
3	Mogens Rüdiger	26-06	Aalborg University	Professor	Research
4	Anonymous 2	30-06	-	-	Government
5	Poul Erik Morthorst	03-07	Technical University of Denmark	Professor	Research
6	Pier Stapersma	03-07	Clingendael International Energy Programme (CIEP)	Senior Researcher	Research
7	Ignacio Marti Perez	06-07	Technical University of Denmark	Head of Division Wind Energy Materials and Components	Research
8	Erik van der Vleuten	07-07	Technical University Eindhoven	Professor	Research
9	Ekaterina Moiseeva	09-07	Nord Pool	Market Monitoring Analyst	Industry
10	Bo Riisgaard Pedersen	10-07	Consulate General of Denmark in Silicon Valley	Energy Sector Expert	Government
11	Mary Thorogood	13-07	MHI Vestas Offshore wind	Senior Specialist, Business Development	Industry
12	Anonymous 3	21-07	-	-	Government
13	Aidan Cronin	23-07	Siemens	Advisory Specialist Wind Power	Industry
14	Peter Markussen	23-07	Energinet	CEO Assosiated Activities	Government
15	Eize de Vries	28-07	Windpower Monthly	Technology and Market trend consultant	Industry
16	Morten Pindstrup	30-07	Energinet	International Chief Engineer	Government
17	Thomas Egebo	04-08	Energinet	President and CEO	Government

Data analysis

All interviews were summarized (see Appendix B) and coded. Deductive coding with variables, as explained by Boeije and Bleijenbergh (2019) was used to analyse the data. This method involves identification of variables in text fragments throughout the interviews. Insights on identified variables were aggregated and a key message per variable was formulated. To break down the process into manageable pieces, the interviewees are divided into three sub-groups: governmental organizations (expert 2, 4, 10, 12, 14, 16 and 17), industries (expert 1, 9, 11, 13 and 15) and research institutes (expert 3, 5, 6, 7 and 8). Often recurring variables per sub-group were outlined and a take-away message per variable and subgroup was formulated. An example of the coding process of the interviews is presented in Table 2 below. The example illustrates how different fragments of interviewees from the 'industry'-group were placed under one variable, and how insights per variable were summarized. Variables needed to be mentioned by at least two interviewees per sub-group to be placed in the final matrix to ensure that a variable does not present the opinion of just one expert. The main outcomes of the coding process are presented in a matrix in Appendix C. This matrix presents the sub-groups on the y-axis and the identified variables per sub-group on the x-axis. The key insights per variable are also outlined in a code tree (see Appendix D). Using a code tree helps to structure the obtained insights per variable rather than per sub-group and to assess how concepts are interrelated (Boeije & Bleijenbergh, 2019). The narrative of the result section is based upon the findings of this matrix and code tree. Quotes are further used to support the argumentation, provide context and deepen understanding. Additionally, insights from the interviews were used to formulate practical and strategic implications and policy recommendations, as the experts had a clear vision on how to move forward.

Table 2

Coding of interviews

<table>
<tr><th>Interview</th><th>Quotation</th><th>Subtheme</th><th>Summary of expert group</th></tr>
<tr><td>I11</td><td>"Northern European operators are important players in the wind turbine market. Important players are the three turbines manufacturers, cables, foundation, towers, blades, for electronics in the turbines, smaller manufacturers. All of these items are mainly concentrated in Northern Europe, especially in Germany, Denmark, the Netherlands but also Spain."</td><td>Cooperation on supply chain</td><td rowspan="3">In Northern Europe we see cooperation on supply chain of wind turbines, but that's not the same everywhere in the world. Cooperation can be beneficial for optimization of the supply chain.</td></tr>
<tr><td>I13</td><td>"Big wind energy companies are getting together. There is a huge collaboration between the companies active in this field. Collaboration can optimize the volume of components, lead to lower price and higher quality."</td><td>Cooperation on supply chain</td></tr>
<tr><td>I15</td><td>"Cooperation on the supply chain of wind turbines differs per country. Some countries try to localise production. For example, in Taiwan, governments create production targets of components that need to be produced domestically. Localising the supply chain creates job opportunities and helps national economies to grow. Especially for developing countries, internalising industries can have a lot of advantages. For countries such as the Netherlands, origin of the components of wind turbines is less important."</td><td>Cooperation on supply chain</td></tr>
<tr><td>I11</td><td>"Denmark has a lot of know how in the supply chain. Not just on turbines but also other components. That is a business that will go to new markets and that they can export. They use embassies and ambassadors to trade. They use existing connections but they are also very good in building new ones. Denmark also sees this as an opportunity to gain influence. Denmark really punches above its weights for a very small country on energy policy. What they do is targeted, they pick their areas and that is what they do."</td><td>Cooperation through knowledge sharing</td><td rowspan="2">Denmark is actively exporting knowledge to take wind industry to next level and gain market share in foreign countries</td></tr>
<tr><td>I15</td><td>"Denmark has a very strong position in the wind energy sector. Big companies such as MHI Vestas are Danish (also partly Japanese). Furthermore, Denmark has many knowledge institutions, engineering firms, a technical university. So, despite Denmark's small size, they play a very important role in the industry. Denmark is also trying to gain market share in countries where wind is not big yet. They help these countries by sharing knowledge."</td><td>Cooperation through knowledge sharing</td></tr>
</table>

Case comparison (sub-question 3)

This chapter entails the main analysis of the study and consists of two parts. First, the differences and similarities between interstate energy relations of Denmark in 1990 and 2018 are outlined. These differences and similarities are based on the findings of sub-question 2. Second, the relation between the independent variables (technical and geographical characteristics) and the dependent variables (interstate energy relations) is determined. The main question that is answered is: to what extent can the observed changes in interstate energy relations be attributed to the geographical and technical characteristics of wind energy? Each of the shifts in interstate energy relations is discussed separately and for each identified shift is determined whether it can be attributed to the characteristics of wind.

Data to answer this sub-question mainly stems from interviews. Some of the interviewees were literally asked whether they thought that shifts in interstate relations could be attributed to the characteristics of wind power (see Appendix B). Answers to this question were used to get a first insight into the factors that were assumed important by experts from the field. Desk research into contextual factors was done to complement the information and examine what other factors could have played a role. The established relations were not based on any academic theory since explaining theories are lacking in this new field. Reliability of the outcomes of this section are therefore limited.[8] Yet, the aim was not to create a new relation but to contribute to the construction of a large number of case studies on which theories might be built in future.

Practical and strategic recommendations (sub-question 4)

This last section translates the main findings of the research into concrete practical and strategic recommendations for Denmark. The aim of this last section is to create understanding of the new geopolitical challenges that Denmark is facing in its renewed energy system. The practical recommendations concern the increasing share of wind power in the electricity system. The strategic implications mainly focus on geopolitical issues. Outcomes of the desk research and, more important, outcomes of expert interviews were used to distract these implications. Thanks to their extensive experience in the electricity field, experts oversee the implications of the transition, strategic challenges and practical difficulties.

[8] Reliability of the outcomes is further discussed in the chapter 5, section 5.3.1.

Table 3

Research methods per sub-questions

Research question	Data required	Method used	Limitation to approach
1. Theoretical background	• Literature on geopolitics, geopolitics of conventional energy sources and geopolitics of renewables • Framework of analysis: literature applied to wind energy • Operationalization	Literature review	Operationalization can be difficult since many of the aspects have not been measured before because of 'newness' of topic.
2. Framework application	• Technical, geographical and economic characteristics of energy system in 1990 and 2018 • Interstate energy relations (energy security, policy considerations and patterns of cooperation and conflict)	Literature review, desk research, semi-structured expert interviews	Might be difficult to obtain required information, for example on the system in 1990 because information is not available, or because experts do not have the required background or knowledge. Risk that experts have contradicting opinions on certain issues.
3. Case comparison	• Comparison of the outcomes of before and after case concerning interstate energy relations • Determine the extent to which changes between cases can be attributed to characteristics of wind or to contextual factors	Desk research, semi-structured expert interviews	Contextual factors are unlimited. Difficult to decide which ones are important enough to be included. The relation between observed changes and characteristics of wind is not scientifically underpinned and is affected by the authors bias.
4. Practical and strategic implications	• Implications of the current Danish situation on a practical and strategic level for the Danish government	Desk research, semi-structured expert interviews	Implications are based on single examples of experts and not validated.

2. Theoretical Framework

This chapter includes a review of the literature on the general concept of geopolitics, geopolitics of fossil fuels, and renewables in particular. The chapter starts with an introduction and definition of the concept ‘geopolitics’. Consequently, geopolitics of fossil fuels and geopolitics of renewable energy are outlined and discussed. The subsequent part of the chapter introduces the framework of analysis, which is used to assess geopolitical implications of wind energy in Denmark. The last section, section 2.3, operationalizes the concepts.

2.1 Geopolitics of energy

2.1.1 Defining geopolitics

Before going into the geopolitical impacts of energy it is important to understand the concept of ‘geopolitics’. Geopolitics has always been a crucial element in national strategies throughout history (Campos & Fernandes, 2017). There is, however, a variety of definitions, largely depending on the context and time in which the term is used. This section therefore starts with a short history of the concept and provides the definition that is used in this study.

The term ‘geopolitics’ was firstly coined by a Swedish political scientist, Rudolf Kjellen in 1899 (Tuathail, 1998). He explained it as the research area in which geographical factors define the power and role in international affairs of countries (Ole & Austvik, 2018). The start of the study field was that geography created different sorts of societies and cultures as their spatial dimensions involved specific opportunities and limitations. According to Kjellen, key elements of this, later called ‘classic’ geopolitics, are the concepts of power and space (Grivach et al., 2017). Decades later, during World War II the focus of geopolitics shifted towards the military field. During that time, the term was associated with the Nazi policy goal of ‘more living space for the German nation’ (Tuathail, 1998). Thereafter, the concept was abandoned by researchers for decades, since they claimed that it concerned geo-ideologies, like Nazism, rather than true geopolitical science (Ole & Austvik, 2018). It was after the break-up of the Soviet-Union that the concept enjoyed a revival of interest. Policy makers, academics, strategic analyst and international managers used it to deal with local and regional dynamics in context of the global system as a whole. From then on, ‘classic’ geopolitics became a manner to study the development of power relations between various political fronts, taking into account their geographical characteristics (Grivach et al., 2017).

In the early 1990’s, an opposing view on the ‘classic’ geopolitics arose. This was the view of ‘critical’ geopolitics (Power & Campbell, 2010). This new group of academics was described by Ó Tuathail as “no more than a gathering place for various critiques of the multiple geopolitical discourses and practices that characterize modernity” (Jones & Sage, 2010, p. 316). Although there is no strict delineated definition of what critical geopolitics entails (Power & Campbell, 2010), there is a common vector of critique. This concerns geopolitics being presented as an objective or practical description of ‘how the world is’, without considering social construction of the concept and its cultural embeddedness (Tuathail, 1998). Supporters of critical geopolitics thus plea amongst others, for a use of the concept geopolitics in which context factors play an important role as well. Furthermore, there is a great deal of criticism on various aspects of the concept.

The comprehensive character of critical geopolitics complicates usage of the term and leaves great space for interpretation of the author. To ensure a common understanding of the concept amongst readers, this study therefore sticks to the more classical definition, in which a component of critical geopolitics is included. This definition is, among others, given by Overland (2019). He defines geopolitics as follows: “Geopolitics is about the influence of geography on the power of states and international affairs, with emphasis on the strategic importance of natural resources, their location, transportation routes and chokepoints" (Overland, 2019, p. 36). Although power has been, and still is, an essential part of the concept, the aim of this study is not to examine whether Denmark has gained (or lost) power due to the increasing share of wind energy. This study merely wants to map whether and how interstate energy relations have shifted over time. The definition that is used in this research does therefore not include the concept of power. It is defined the following: "Geopolitics is about the influence of geography on international relations, with emphasis on the strategic importance of natural resources, their location, transportation routes and chokepoints". The following sections describe geopolitics of both fossil fuels as renewables energy.

2.1.2 Geopolitics of fossil fuels

After defining the term geopolitics, the geopolitical implications of conventional energy sources can be discussed. Geopolitics of energy have been mostly centred around fossil fuels. This focus on fossil fuels stems from their dominance in the past, and current energy mix (Scholten, 2018). In 2016, still 87 percent of the world energy use was produced by fossil fuels (Ole & Austvik, 2018). It is important to understand how fossil fuels have influencing geopolitics for two reasons. First, due to rising global energy demand, fossil fuels are assumed to keep playing a pivotal role in the coming decades, meaning that renewables are not influencing geopolitics on their own. Second, in-depth understanding of insights from the field of geopolitics of fossil fuels form a solid knowledge base on which to go forward. The following of this section describes some of the most important characteristics of fossil fuels through which they have been impacting interstate energy relations.

Fossil fuels are geographically bounded and can only be found in certain areas. The geopolitical factors stem from this mismatch of location between consumption and production (Masuda, 2007). High geographical concentration allows for control over fossil fuels, which in turn can incite competition over resources. Geopolitics of conventional energy sources is therefore characterised by clear centres of power on both the supply and demand side (Paltsev, 2016). It links to the security of demand for exporters and security of supply for importers (Ole & Austvik, 2018). The geographic distribution of fossil fuels has led to certain trade patterns between countries. Electricity generation takes place in large, centralized power plants, mostly far from consumption areas. Complete control over generation is possible so that generation can be adapted to demand. Moreover, the ability to store fossil fuels allows countries to have strategic reserves. The gaseous, liquid and solid nature of fossil fuels makes it possible for them to be transported through a variety of means and via different routes. Pipelines, rails, tankers and roads are each suitable options to transport fossil fuels all over the world. This allows for interstate energy relations between countries all over the world. The great diversion in trade options and routes makes these options less vulnerable to be attacked.

These geographical and technical characteristics of fossil fuels have influenced national energy policies. Countries have made energy strategies meeting their energy needs and securing their international position. The safeguarding of energy needs have influenced international energy relations significantly. The rise of great powers, the emergence of conflict and war between countries and the formation of alliances, are all examples of energy related mechanisms.

2.1.3 Geopolitics of renewable energy sources

The ongoing energy transition raises questions about the geopolitical implications of the increasing share of renewables in the energy system. Most of the characteristics of renewables are significantly different than the earlier described characteristics of fossil fuels. This leaves countries with unanswered questions. How are energy trade relations affected by the higher share of RES? Are renewables going to reduce conflicts between states or are they going to stimulate cooperation? Can countries leading the renewable energy transition enhance their position in the international field? The following section aims to discuss the literature on questions such as these. Before doing so, however, we need to specify the term renewables. For renewable energy, we use the definition as given by the

International Energy Agency (IEA), which is as follows. Renewable energy is 'energy that is derived from natural processes that are replenished constantly such as solar, wind, biomass, geothermal, hydropower, ocean resources (tidal and waves), and biofuels, electricity and hydrogen derived from those renewable sources" (International Energy Agency, 2004, p.12). Geopolitics of renewable energy in particular, is about how the geographical and technical characteristics of renewables form interstate energy relations between countries (Scholten, 2018).

Especially among Northern European researchers, renewed attention for the geopolitical implications of renewables can be observed (Vakulchuk et al., 2020). Various academics make projections about the implications of renewables and identify components through which RES can reshape geopolitics. Different perspectives seem to be used to examine these implications. On the one hand, academics centre the discussion around power, and the influence of states relative to each other. One of the key questions within this debate is who will be the new winners and losers of the transition. Various authors such as IRENA (2019), Overland et al. (2019) and Smith Stegen (2018), try to classify countries into potential losers and winners. They predict whether nations' positions will strengthen or weaken in a renewable energy system. On the other hand, there is the perspective used by Scholten (2018) which merely tries to outline the newly arising connections, relations and patterns of interactions between states. The major goal pursued by this perspective is to outline new interstate energy relations. It is a systemic description of the features of the new game rather than an indication of potential winners or losers. While both perspectives are closely related, there is a significant difference between them: the first perspective does not only outline implications, it also estimates future developments based on the observations. The second perspective, on the contrary, merely tries to outline observations without forecasting future positions.

The latter perspective is used in this research. Not Denmark's relative position in the future energy field is examined but an outline of the shifting international energy relations and interdependencies is presented. Doing so requires examination of how characteristics of renewables are likely to influence these interstate energy relations. Several issues around which the implications of renewables are centred, have been identified through literature review (IRENA, 2019; O'Sullivan et al., 2017; Scholten et al., 2020; Scholten & Bosman, 2016; Vakulchuk et al., 2020). Five major themes are assumed to be relevant for this study: interstate dependencies, regionalization of energy trade relations, critical materials, know-how knowledge and cyber security.[9]

Interstate dependencies

The geographical distribution of energy sources has serious impacts on relations between countries in fossil fuel-based energy systems. The scarce and geographically concentrated character of natural gas, oil and coal gives countries control over energy flows and allows them to strategically use these sources (Scholten & Bosman, 2016). Some countries being better endowed with fossil fuels than others, creates certain dependencies between countries and largely impacts the geopolitical position of these countries in the international field. Vakulchuk et al. (2020) therefore assumes that interstate dependencies are high in a fossil fuel based system. These arising interstate dependencies might even lead to tensions or conflicts between nations (Månsson et al., 2014). This can for example be seen in energy rich areas such as the Middle East or Venezuela, where oil conflicts took place frequently. Not only between countries, but also within countries this can lead to political instability.

[9] While there are more themes to distinguish, this research intentionally limits it selves to themes that directly affect interstate relations. Other relevant themes are for example, the assumed democratisation of countries or local conflicts over land use. These have topics been left out since they concern consequences within states rather than between states.

The chance that renewables are going to be used as strategic good or as objective of conflict is, however, smaller (Månsson, 2015). In contrast to fossil fuels, renewables are abundant and distributed around the globe. Most countries possess a certain form of renewable energy, offering them the opportunity to produce renewable power (Scholten et al., 2020). Domestic production of energy enables countries to reduce their energy import dependency and enhance energy security (IRENA, 2019). The abundant nature of renewables makes it impossible to control them, and they are therefore less likely to lead to interstate dependencies. Instead, Scholten (2018) assumes that countries face a make-or-buy decision, in which they have to choose between securing domestic production or importing cheap electricity. This decision mainly depends on whether countries' national capacities are large enough to meet their energy needs, what options they have for cheap imports and how reliable their trade partners are. It is assumed that producer countries are concerned about security of demand and desire to maximize revenues, that consumer countries want to secure their supply and offer affordable electricity, and that transit countries try to retain their position and create some political or financial leverage (Scholten, 2018). Interstate dependencies are likely to be low if countries produce renewable energy domestically, they are high if countries import (cheaper) renewable energy (Vakulchuk et al., 2020).

Regionalization of energy trade relations

Since electricity is the main energy carrier of most renewables, one can expect electrification of the system (IRENA, 2019). Electricity currently accounts for around 19% of the total energy consumption but electrification of various end-use sectors, such as transport, heating and cooling, is presumably going to increase the demand for electricity. Hence, long-distance trade of fossil fuels will diminish and regional cross-border trade of electricity is likely to increase (Schmidt et al., 2019). Scholten et al. (2020) describe this as a regionalization of energy relations in which global energy networks shift towards regional and continental systems. Regionalization of trade relations induces a significant shift in trade routes and partners and has some serious geopolitical implications. Electrification can facilitate interstate cooperation in the form of grid communities, which are countries physically connected by the grid, which allows for collaboration between transit, consumer and producer countries (Scholten & Bosman 2016). Guler et al. (2018) call such a collaboration a 'Regional Energy Hub'. In such a geographical area, the boundaries of the country are determined by potential electricity energy sources, rather than by the political borders. The underlying assumption of an energy hub is that neighbouring countries with mutual beneficial energy mixes can benefit from cooperation to overcome common challenges (Guler et al., 2018). Countries in a particular area can cooperate through common interest projects such as interconnection capacity investments. Increasing transmission capacity can not only induce reductions in generation costs and emissions, it can also add flexibility to the system. Evidence of these forms of collaboration are already given by Northern European countries, which are cooperating on renewable energy production (Gullberg, Ohlhorst, & Schreurs, 2014). Månsson (2015) also highlights the incentive for cooperation between countries by means of grid and market integration. International electricity trade is likely to strengthen bilateral or multilateral cooperation since there is a mutual interdependency between exporter an importer, in which the importer relies on electricity and the exporter on revenues (Månsson, 2015; Overland, 2019). Mutual benefits, trust and understanding are considered essential requirements for fruitful cooperation (Hong, 2010; O'Sullivan et al., 2017; Scholten & Bosman, 2016).

Electrification of the system can, however, also have undesirable geopolitical implications. Absence of the aforementioned requirements for cooperation can induce or aggravate political unrest between countries (Smith Stegen, 2018). Exporting countries are, for example, able to use electricity cut-offs as a policy tool (Johansson, 2013b; Moore, 2017). Moore (2017) gives the example of Morocco which partly depends on Algeria for its electricity. Algeria could use supply cut-offs as political tool because of ongoing political tensions between the two countries. Another example is Nepal, which increasingly depends on India for its electricity supply while friction between the two countries is growing. Electricity might in these cases be used a political weapon that aggravates tensions. Furthermore, grid communities have the potential to contribute to a fragmented multipolar electric world (Scholten et al., 2020). In regional power blocks, interregional connection is unlikely due to the fear of dependence. The fact that these regional blocks are all organized separately, makes them vulnerable for attacks.

Critical materials

Another major geopolitical implication is that the use of critical materials for clean technologies, might increase competition between countries (Scholten et al., 2020). Manufacturing of renewable energy technologies requires serious amounts of critical materials (Scholten & Bosman, 2016). According to the European Commission (2010), raw materials are called 'critical' when they have a higher risk of supply shortage and when their impacts on the economy are higher compared to other raw materials. They published a list in which they label 14 raw materials as critical. The list consists of raw materials (such as cobalt and magnesium), Platinum Group Metals (PGMs) and Rare earths. Dependence on these critical materials might be problematic for importing countries since supply is becoming more difficult, especially for European countries (Massari & Ruberti, 2013). Countries possessing these materials can, use the materials as strategic goods. Cartels could then develop around the critical materials which might provoke tensions or conflicts (O'Sullivan et al., 2017). The extent to which geopolitical tensions are truly going to arise around critical materials is still uncertain. While some researchers assume that critical materials will form a major threat for countries security, others think that the geopolitical influence of critical materials is overestimated. Overland (2019) acknowledges the possibility that these materials are going to be costly and that they might become a great source of income for exporting countries. That does, however, not inevitably lead to a geopolitical race to take over control over these resources. Månberger & Johansson (2019) emphasize the importance of substitutes for critical materials construction of renewable energy technology. Substitutes can significantly reduce the dependence on critical materials. Next to that, diversification of supply chains is considered to be key to ensure stable supply of these sources (Massari & Ruberti, 2013).

Know-how knowledge

The energy transition from fossil fuels to renewable energy sources bolsters the role of technology (Criekemans, 2018). The major challenge is no longer to have access to resources but to convert these resources into energy at competitive costs (Bonnet, Carcanague, Hache, Seck, & Simoën, 2019). Therefore, the role of technology becomes increasingly important. One of the areas in which the geopolitical role of technology is reflected is in international climate negotiations (O'Sullivan et al., 2017). Countries' willingness to ratify international climate agreements to reduce emissions depends, among others, on their level of the development of clean energy technologies. It is hence likely that different technological development levels, or intellectual property rights will be a source of contention between countries (Bonnet et al., 2019; Scholten et al., 2020). Countries with high technological development levels and many intellectual property rights see these international climate agreements as a way to gain international market share, while countries with lower levels might see them as threat to their energy security since they do not possess the right technologies.

Cyber security

Another increasingly discussed issue of renewable energy systems is the possibility of cyber-attacks. Several academics, think tanks and security organizations fear that terrorists will hack computers, required to manage intermittency, to disturb control utilities or grids (Månsson, 2015). The trend of digitization and the increased dependence on these digital control systems hence increases the exposure to cyber threats (Månsson, 2015). The extent to which cyber-attacks form a true threat and are going to be used as political weapon is still unknown. On the one hand, there is an increased vulnerability for cyber-attacks due to digitization of electricity network (Liu, Xiao, Li, Liang, & Chen, 2012; Onyeji, Bazilian, & Bronk, 2014). On the other hand, the impact might not be as harmful as is currently expected. IRENA (2019) acknowledges the increased risk of cyber-attacks but argues that the risk should be placed in perspective. Cyber risks are not unique to renewables, they exist in all different types of digital systems. Effective counter measures can be created to decrease the risks. Overland (2019) highlights the fact that developed countries already rely on digitally organized electricity grids for decades. The risk to cyber-attacks is thus not new and the expected threats should not be overstated.

In conclusion, while various projections on the potential geopolitical implications of renewables have been made, finding out how they exactly affect international relations is mainly a matter of time. Månsson (2015) already concludes that the risk of interstate conflicts is lower in a renewable energy system than in fossil fuel-based energy system, but that the risk of local instabilities increases. Real life cases are, however, needed to generate better understanding of the shifting interstate energy relations and the patterns of cooperation and conflicts that might arise due to the increasing share of renewables in the system. The following of this study will therefore focus on the case study of Denmark.

2.2 Framework of analysis

The previous section has outlined some central themes through which renewables might reshape interstate energy relations. As argued in the conclusion, it is simply too early to draw final conclusions on the geopolitical impacts of renewables and real-life cases are needed to deepen understanding. This section therefore introduces the framework of analysis that will be used in this research to assess the implications of wind power in the electricity system in Denmark.

The study area of geopolitical implications of renewable energy integration is a relatively new academic field. Most of the existing frameworks and concepts to study energy geopolitics are focussed on the characteristics of fossil fuels. A comprehensive framework to systematically approach and examine the geopolitics of RES was lacking. Scholten (2018) therefore constructed a framework that helps to study the relation between geographical and technical characteristics of renewables and their geopolitical implications. The framework aims to break down the topic into manageable pieces that can structure the debate. It entails four different steps. The first step is about identifying the technical and geographic characteristics of the renewable system. Moving along the supply chain allows to structurally outline what the electricity system looks like and what its main characteristics are. The second step investigates the economic impact of renewables. This step aims to outline how the geographical and technical characteristics of the electricity system have influence on the economic part of the electricity system. The third step involves the interstate energy relations between countries that might change because of renewables. The geographical, technical and economic characteristics of the system are assumed to induce new patterns of cooperation and conflict and therewith influence interstate energy relations. The last step examines the relation between the first step and the last step. The goal of this step is to assesses to what extent the findings in step 3 can be attributed to the observed system characteristics in step 1 or whether there are other explaining contextual factors. Examples of these broader contextual factors are developments in a social, economic, environmental, operational, technological situation. The first three steps of the framework, as created by Scholten (2018), are presented in Figure 2. The next section described how the framework of Scholten is used as input for the constructed framework of this study.

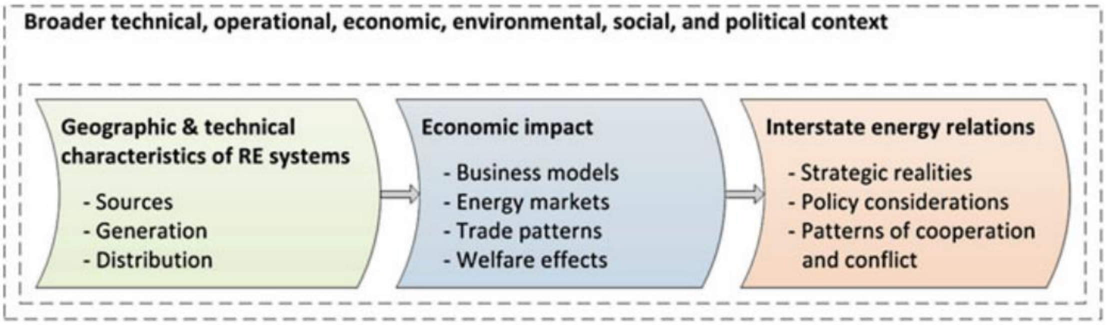

Figure 2. Framework of analysis. Source: Scholten (2018)

2.2.1 Framework adaptation

Scholten (2018) has not only distinguished the four steps of the framework, he also identified concrete variables to outline implications for each step. His framework however focuses on renewable energy systems in general rather than on wind energy system in particular. Besides, his framework adopts a global, rather than a local or country specific perspective. Since this study focusses on a specific country and on a specific form of renewable energy, a more specified framework is required. The somewhat general variables as distinguished by Scholten (2018) are therefore adapted to the case of wind power in Denmark. They will be critically analysed and reassessed on their suitability for this study. Consequently, variables considered (ir)relevant by the author are left out or added. For each variable, a concrete indicator to measure the variable is defined. The framework of Scholten (2018) is hence used as a starting point to create a new, more specified framework. Figure 4, at the end of section 2.2, presents the adapted framework. The method used to construct the framework can be found section 1.4.2.

The following of this chapter is structured as follows. Sections 2.2.2 until 2.2.4 provide the theoretical framework on the technical, geographical, economic characteristics and interstate energy relations. A rationale is given of why certain indicators are added. Section 2.3 presents the operationalization tables of all components to be measured. This section also summarizes the most important rationales for altering or adding certain variables to the framework of Scholten (2018).

2.2.2 Geographical and technical characteristics

The independent variable of the framework encompasses the identification of the geographical and technical characteristics of the energy system. Geographical characteristics are the naturally created features of the system, features created by the earth. One could say, the geographical characteristics determine the natural context in which the technical system is embedded and shaped. Looking into these characteristics is the starting point of the analysis. An appropriate manner of dealing with the geographical and technical characteristics is by moving along the supply chain, starting by the source to generation to distribution (Scholten & Bosman, 2016). As stated earlier, this research does not take the consumption of electricity into account. Especially those geographical and technical characteristics that differ significantly in wind energy systems compared to fossil fuel dominated systems, are discussed. Figure 3 presents some of the major differences between fossil fuels based and renewable energy systems.

Sources

The first step in the supply chain is the source. In conventional electricity systems the source consists of fossil fuels such as coal, gas or oil. These sources are extracted from the earth, transported to power plants, burned, and the produced steam is used to generate electricity. In wind energy systems, wind is the energy source. Wind is captured by wind turbines and kinetic energy is turned into electricity (Scholten & Bosman, 2016).

First, it is of interest to investigate the **geographic location of energy sources**. The geographical distribution of fossil fuels differs significantly from that of wind. Fossil fuels are scarce and geographically bounded, they can only be extracted in specific areas. Wind on the other hand is abundant and allows for domestic electricity production in every part of the world. Despite its abundant character, wind conditions are not the same across the globe. Like with fossil fuels, certain countries are better endowed than others (Scholten & Bosman, 2016). For fossil fuels this means that some countries possess oil, gas or coal reserves, allowing them to use it for own consumption or to export it. For wind energy this means that some countries have more favourable geographical conditions to generate wind power than others. These countries can therefore produce low-cost electricity, and one would expect that electricity production shifts to those countries that are able to harvest wind most efficiently (Scholten & Bosman, 2016). To assess the wind energy potential of selected sites in certain countries, average wind speed and average wind power density are important characteristic that must be considered. Long-term analysis of these wind characteristics, obtained by a metrological station, is required to determine the suitability of a certain site location (Mahmood, Resen, & Khamees, 2020).

Second, probably the most important difference between wind and fossil fuels is the **intermittent** character of wind, compared to the **stable** character of fossil fuels. Wheras fossil fuels can be extracted at a steady rate, renewables cannot. This might cause technical friction when wind is integrated in the system. To maintain balance between production and consumption of electricity, fossil fuel dominated systems can, thanks to their stable and predictable deployment rates, react to the varying electricity demand (Denholm & Hand, 2011). By ramping up or down the power plants, electricity production can be regulated, and system balance is maintained. Wind power does however only allow for control of production through curtailment. According to Verzijlbergh et al. (2017), intermittency refers to two specific characteristics of RES: *variability and uncertainty*. The former is about the variability of atmospheric processes which causes large fluctuations in wind power generation. Production output is largely weather dependent and difficult to control. The latter, uncertainty, is related to the unpredictability of weather. Prediction models are therefore used to forecast the amount of electricity that is likely to be generated at a certain moment in time. Despite the major improvements in modelling techniques, there will always exist a difference between weather forecasts and realizations (Verzijlbergh et al., 2017). Balancing wind power production by managing wind's variability and the forecasting difficulties is among the most important challenges of wind integration (Jonan & Tørnæs, 2017). The extent to which a source is variable is extremely difficult to assess and there is no consistent way to do so (Tran & Smith, 2017). It can, for example, be measured on different (time) scales, and there is a broad range of aspects that can or cannot be included. There are significant differences in the extent to which a source is variable. Various attempts have been made to compare the variability and predictability of sources to each another. The different conditions such as area characteristics and terrain complexity have too much influence on the outcome. It is hence impossible to generalize findings or the extent to which a source is variable (Widén et al., 2015). This study therefore merely describes whether or not the source is variable.

It is furthermore essential to assess a nations' **generation potential**.[10] While each country has some form of renewable power, the extent to which countries can generate electricity from those renewables varies greatly. This generation potential depends on numerous aspects. Hoogwijk et al. (2004) distinguish three categories to assess this potential: the technical, economic and geographical potential. In this study we take the latter, the geographical potential, to assess the extent to which

[10] One might argue that generation potential needs to be placed under 'generation'. It is, however, placed under 'source' since it is an alternative for Scholten's (2018) variable of ability to meet demand.

Denmark is able to meet demand by domestic generation.[11] The geographical potential has to do with the total amount of available land to generate electricity, taking the geographical constraints into consideration (Hoogwijk et al., 2004). The amount of available land to build wind turbines on is restricted by various aspects, such as buildings, infrastructure and protected areas (Enevoldsen et al., 2019). Thus, the geographical generation potential for renewables generates insight in the generation possibilities concerning geography. For fossil fuels, generation potential can be assessed by looking into the number of available reserves and the production and consumption ratios.

Another geographical characteristic that is relevant for wind energy systems is to assess whether a country has a **coastal area.** The previous variable, generation potential, only assesses potential on land. This potential can, however, be significantly increased if wind turbines are located offshore as well. Offshore wind turbines have a more stable generation output and offshore wind speeds are generally higher. This variable therefore assesses the length of a nations' coastal area.

Generation

The used **technology and its lifetime** to generate electricity plays an important role in the geopolitical implications of the transition (Criekemans, 2018). According to Criekemans (2011), many of the technologies used to produce renewable electricity are so complex that international cooperation is required for their construction. He calls the transition towards renewable energy technologies a technological revolution. Especially wind and solar power sectors are undergoing significant technological innovations. Cross-border cooperation and foreign trade can accelerate innovation process in these clean-energy sectors. It is hence important to understand what type of technologies are used so that one can generate insight into new supply chains and forms of collaborations or conflict.

The second aspect that must be considered is the (**de)central character of generation**. Central generation consists of large-scale power plants, mostly operated by large energy companies (Hvelplund & Djørup, 2020). Transport over long distances is required and high transmission investments are needed for these central power plants. Most of the large fossil fuel power plants are centrally regulated. Decentral power generation, on the other hand, can be described as power generation within the distribution network. It includes small-scale technologies, often close to consumption locations (Newbery, Pollitt, Ritz, & Strielkowski, 2018). Decentral generation offers consumers the possibility to produce electricity by themselves and meet local needs, for example by connecting PV solar panels. The increase of renewable energy sources leads to a more decentralized energy system (Newbery et al., 2018). The shift towards a more decentral energy system largely influences the operational requirements of electricity systems. Decentral generation asks for more local operation, it might influence business models and can lead to local empowerment (Scholten et al., 2020). This local and decentral operation might also add a new geopolitical layer to the current system (Hache, 2018).

Next to the generation itself, also the production technologies used to generate electricity differ in wind energy systems from fossil fuel-based systems. Manufacturing of crucial components of wind turbines often requires **critical materials.** The European Commission (2010) established a list of 14 raw materials that are labelled as critical.[12] Next to raw materials, this list consists of platinum group metals[13] and rare earths.[14] The latter needs some clarification, these rare earths are not truly scarce, they are

[11] The economic and technical potential are important to consider as well. The limited scope of this study does however not allow to include everything. The geographical potential has been chosen since the economic and technical potential are be partly captured under economic impacts and technical characteristics.
[12] Critical materials include antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, Platinum Group Metals, rare earths, tantalum, and tungsten.
[13] Platinum Group Metals refer to platinum, palladium, iridium, rhodium, ruthenium and osmium.
[14] Rare earths involve yttrium, scandium, lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium.

actually quite abundant. They appear, however, in such small proportions that mining solely for them is often not viable (Brumme, 2014) and environmentally unfriendly. Furthermore, critical materials are not equally spread around the world nor do countries have an equal ability to withdraw them. The asymmetrical dispersion makes their supply subject to vulnerabilities and allows for strategic use by exporting countries (Brumme, 2014; Massari & Ruberti, 2013). Situations in which supply might be disrupted are large companies trying to gain market power, delays in supply and instability in producing countries. Heavy dependence on these materials can be problematic for importing countries. We must therefore understand the extent to which countries rely on these critical materials to outline potential supply bottlenecks and challenging dependencies (Cao et al., 2019; Massari & Ruberti, 2013).

Distribution

Moving further along the supply chain, brings us at the characteristics of electricity distribution.

We firstly look at **network technology and topology**. The type of network that is used to transport energy sources to power plants and electricity to consumers, differs in wind energy systems and fossil fuel-based systems. Electricity is the main energy carrier in wind power systems, which can be transported through transmission lines. The electric nature of electricity does not (yet) allow for efficient transportation via other means.[15] Due to transportation losses, long-distance trade of electricity is not economically viable (Schmidt et al., 2019). Moreover, all electricity is transported through the same transmission network. Fossil fuels have a solid, liquid or gaseous nature, which allow them to be transported by various means. They can for example be transported via over roads, rails or via shipping. The large variety in transportation routes and means spreads the involved transportation risks. Moreover, long-distance transportation losses are limited so they can easily be traded on a global scale. The nature of the resource and transportation options create therefore different trade opportunities in both systems.

Next to that, one can expect an emphasis on infrastructure operations (grid control) in wind energy systems (Scholten, 2018). In fossil fuel-based systems, oil, gas and coal need to be transported from the extraction location to the generation location. The focus was therefore on commodity supply security. The large variety in transportation routes and means spreads the involved transportation risks. In wind energy systems, all electricity is transported through the same transmission network. Reliable operation of the network therefore becomes increasingly important. The intermittent nature of wind power creates novel operational challenges when wind power is penetrated into the grid. Hence, additional **operating systems** of the grid are required to increase the amount of wind turbines connected to the grid. For example, in order to balance the load with the generation capacity, the system operator must comply with very specific frequency standards of the grid. Integration of intermittent wind asks for additional production reserves to maintain the system performance within the prescribed frequency limits (Ibrahim, Ghandour, Dimitrova, Ilinca, & Perron, 2011). It is outside the scope of this research to go into the specific technical details of the additional grid operation requirements, such as frequency control or voltage control issues. This research will therefore merely focus on more general, deviating operating requirements such as grid reinforcement or smart control.

Another technical component that is important in electrical energy systems largely driven by wind energy, are **storage means.** As wind energy integration in the energy system increases, the need for electricity storage grows (National Energy Technology Laboratory, 2020). While power plants can respond to the varying demand, the instable output of wind turbines cannot be controlled, nor be adjusted to demand (Denholm & Hand, 2011). To prevent from serious imbalances between supply and demand, electricity storage is therefore crucial in wind energy systems (Hadjipaschalis, Poullikkas, & Efthimiou,

[15] Electricity can also be transported through batteries or ammonia. Since this is not yet efficient, these means are excluded in this study.

2009). For this step in the framework, in which the technical components of the system are described, we merely want to assess whether storage is required. The particular storage options are described in the 'energy security' part in step 3.

The next variable is the amount of **neighbouring countries.** As described in the previous section, electricity trade is assumed to be more local or regional compared to trade of fossil fuels due to long-distance transportation losses. Electricity trade relations might hence be restricted by the geographical location of the system and the extent to which the country lies close to other nations. Electricity trade might for example be less economic attractive for a remote island than for a country with several neighbours. Countries without neighbours are more likely to produce electricity themselves rather than import it. Interstate relations can hence be affected by a nations' neighbours.

Another issue that needs to be examined are the **vulnerabilities of the system** through which the system can become a target of foreign physical attacks (Kisel, Hamburg, Härm, Leppiman, & Ots, 2016). Vulnerable energy systems can be attractive targets for physical assaults (Månsson, 2015). Differences in technical characteristics of fossil fuel and renewable energy systems, create different possibilities for attacks. Månsson (2015) distinguishes three issues that can be assessed to examine these vulnerabilities. First, has the system parts of high energy density exposed to attacks? Second, is the system sensitive to the failure of components? Third, does what the system symbolise make the system more attractive to attacks? For example, a symbol centralized political power is more likely to become the target for an attack than a symbol of social inclusion is Description of these three issues helps to assess whether a system is likely to be the target of attacks.

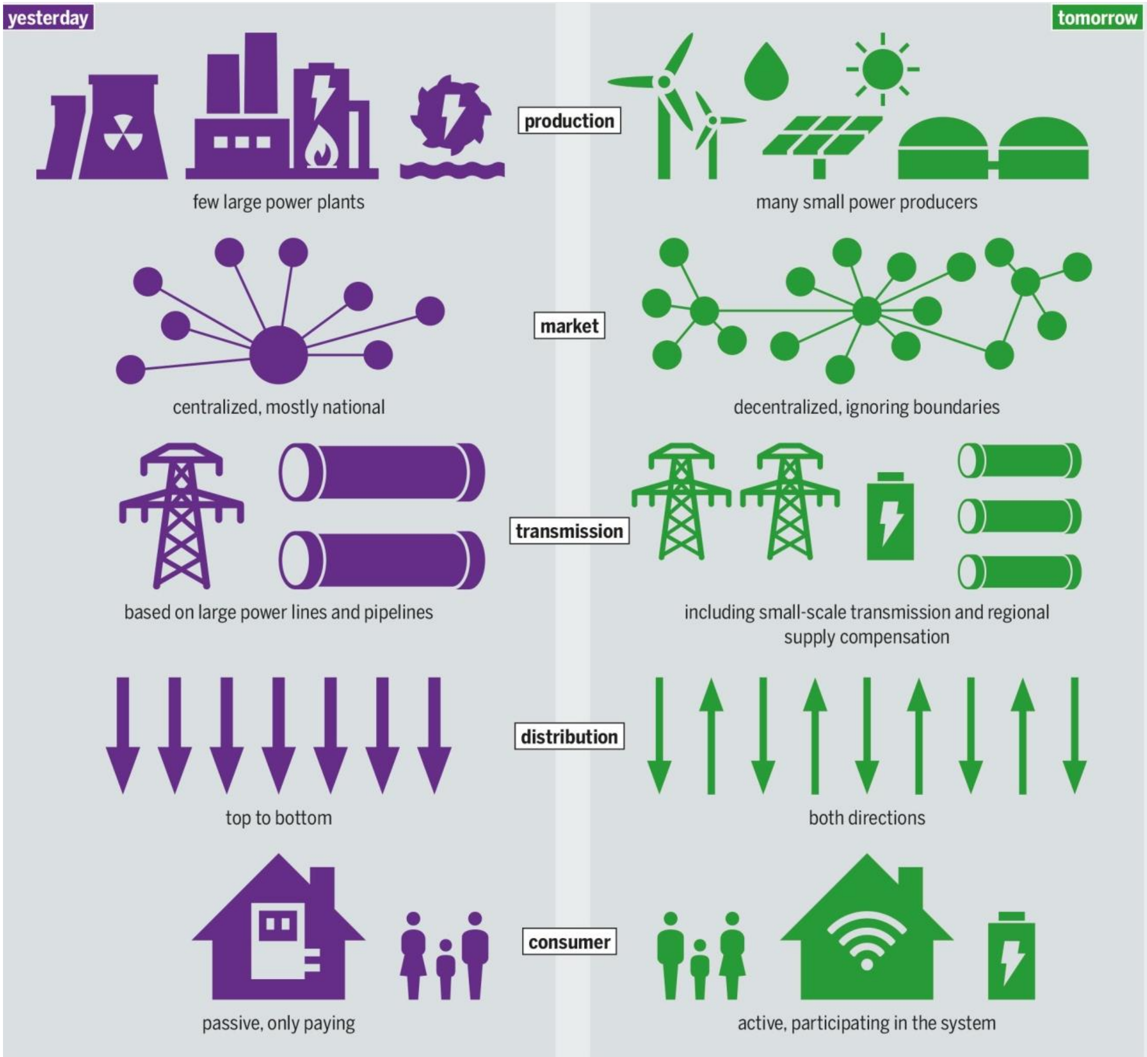

Figure 3. Different technical characteristics of fossil fuel based and renewable electricity systems

2.2.2 Economic impacts

It is difficult to go directly from the geographical and technical characteristics to the geopolitical impact of the system (Scholten, 2018). Scholten therefore argues that it can be beneficial to take an intermediate step and examine the economic impact of renewables on the system. The impact that geographical and technical characteristics of wind energy have on the electricity market structure and trade patterns are therefore examined in this subsection.

Electricity market structure

The first variable that is included is the **market scope**. As explained in the 'distribution' section, fossil fuels can be transported over long distances through pipelines, overseas, in trucks over roads or over rails. Trade possibilities, and the market scope, are thus not limited by a physical transportation network. Electricity, on the other hand, must be transported through electricity wires and through the electricity grid, which is solely possible through an integrated network that physically connects producer and consumer (Scholten & Bosman, 2016).[16] Unlike the most fossil fuels that are traded globally,

[16] Electricity can also be transformed into chemical bonds such as hydrogen and ammonia. These chemical bonds allow for long-distance transportation. Regions that possess abundant supply of green electricity can than transform electricity into chemical bonds and transport it on a global scale. While we see a great potential of this transportation option in the future, it is not included in this study since it not yet used on a large scale. The market scope is thus limited to the physical electricity network.

electricity is traded as regional commodity (IRENA, 2019). It is hence likely that global markets become more regional. Arising electricity trade relations are therefore likely to be local or regional, since they are limited by the grid.

The next variable that must be included is **the number of producers and consumers** on the market. Fossil fuel markets are mostly dominated by large, central players, with a small number of producers. The oligopolistic nature of fossil fuels gave these major players the ability to abuse their market power (Valdés Lucas, Escribano Francés, & San Martín González, 2016). This was for example the case during the oil crisis in 1973, when oil exporting countries declared an oil embargo against European countries (IRENA, 2019). In wind energy systems, the number of producers is likely to increase since every country has, to a certain extent, the possibility to generate wind power (Scholten, 2018). An increasing number of producers induces a more competitive market, in which it is more difficult to use energy as strategic good. Thus, the number of producers and consumers has to do with the symmetry of dependencies. In a system with very few producers or consumers, the dependencies are more asymmetric while in a system with much producers and consumers they become more equal.

Related to the previous variable, is the variable **barriers to entry or exist the market.** If markets have low entry and exist barriers, it enables a large set of actors to participate in the market. More market actors lead to more competition, which makes it more difficult to strategically use electricity. Increasing competition in European electricity markets was done at a large scale at the beginning of the 21st century. Electricity markets were liberalized then, which increased competition. The market entry barriers included in this study are as follows: limit pricing, excluding behaviour, strategic investments, sunk costs, economies of scale and switching costs for consumers.

Another important economic implication of the increasing share of wind energy are energy **price fluctuations** (Verzijlbergh et al., 2017). It seems highly likely that when energy generation is mostly driven by fluctuating weather conditions, energy prices will fluctuate as well. On the other hand, one could argue that wind energy is less vulnerable to price fluctuations since it does not need fuel to be generated (Valdés Lucas et al., 2016). It is hence not affected by price volatility of fossil fuels.

Trade patterns

Trade patterns are the second economic impact indicator that are considered in this study. The transition to a renewable system reduces the use of fossil fuels. Old trade flows might be cut off and new flows might arise.

The first and second variable entail the **trade flows of energy sources and carriers** and **trade flows of materials and products.** To understand what type of new interstate energy relations arise, we must generate insight into the trade relations of Denmark. A distinction has been made between energy sources and carriers on the one hand. These sources and carriers refer to electricity, oil, gas and coal. On the other hand, we distinguish materials and products, which refer to the (critical) materials and components required for construction of wind energy technologies and conventional power plants. Outlining the trade flows helps to generate insight into the 'make or buy' decision that countries are assumed to face, as described by Scholten and Bosman (2016). I. e. are countries going to produce electricity domestically to increase security of supply and decrease import dependence or are they going to import cheap electricity from countries with more favourable production conditions?

The last variable is **interconnections** of the grid. As explained, the trade of electricity is constrained by the physical network. It is therefore important to outline the capacity of the physical interconnections of the grid that enable trade between countries. These interconnections represent the amount of electricity trade that is physically possible.

2.2.3 Interstate energy relations

Step 3 of the framework encompasses the dependent variable. In this step, the newly evolved interstate energy relations are examined. This step consists of three sub steps. The geographical, technical and economic circumstances force Denmark to arrange their energy security in a specific manner. The energy security situation is therefore examined first. Policy considerations and means available to the Danish government to safeguard their energy security must be outlined thereafter. Third, the new patterns of conflict and cooperation induced by these new energy strategies integration of wind energy are mapped.

Energy security

Countries are positioning themselves so they can safeguard their energy security (Criekemans, 2018). Their energy market is designed in such a way that energy security can be guaranteed. If geographical and technical aspects change, the way in which energy security is safeguarded changes as well.[17] Before diving deeper into the discussion of how countries can safeguard their energy security, a definition of this broad concept is required. Energy security has been a paramount issue for decades. It has been one of the main goals of public policy. Its importance stems from the crucial role that energy plays in ensuring economic progress and a well-functioning society (Johansson, 2013a; Kruyt et al., 2009). Governments therefore have an essential role in providing an uninterrupted and affordable flow of energy for its inhabitants. An exact definition that is used for energy security is, however, hard to find. Literature shows that the definition is contextual and dynamic (Ang et al., 2015). It largely depends on the people it is used by, and the environment it is used in. For this study, the energy security definition as created by Azzuni & Breyer (2018) is used. They define the concept as follows: "energy security is a feature (measure, situation, or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats" (Azzuni & Breyer, 2018, p. 5). This definition seems suitable within this research since it aims to assess the 'status' of the two different energy systems (in 1990 and 2018), that are operating optimally. The goal of energy security assessment here is to examine *how* the system is organised to safeguard energy security, rather than to quantitatively assess the level of energy security. We do not aim for a quantitative level of energy security, but we aim to understand the potential interstate relations that follow from a differently organised energy security situation.

Several frameworks exist in the literature that attempt to assess energy security. The major part of literature, however, focuses on fossil fuels such as oil, gas and coal (Valdés Lucas et al., 2016). The concept of energy security has therefore been largely influenced by characteristics of these energy carriers. Since the technical characteristics of renewable system differ significantly from those of fossil fuel dominated systems, most of the existing frameworks are not suitable to be applied to renewable systems. The framework to assess energy security that is used in this research is therefore constructed based on the observed technical, geographic and economic changes in step 1 and 2. The energy security index as created by Sovacool and Mukherjee (2011), in which they distinguish 5 energy security dimensions and 320 simple and 52 complex indicators is used as starting point. From this list, relevant indicators are selected, added or adapted. Additionally, other studies in which energy security of renewable systems is assessed are used as extra source of information. Construction of the energy security index includes the same steps as construction of the previous framework, which can be found in section 2.1. We start with a discussion of the literature on the included components and variables. The operationalization table of all included variables and indicators used to measure the variables, is presented in Table 5 in section 2.3. While reading this section, it is important to keep in mind that the

[17] Scholten (2018) calls this first sub-step strategic realities. He argues that strategic realities of countries can be studied through assessment of energy security. This study therefore refer to this step as energy security, in which an energy security analysis is conducted.

aim of the energy security is to explore any potential insecurities in the Danish system, rather than to assess the extent to which the Danish electricity system is secure.

Security of supply

The first variable is providence of **flexibility options.** In order to deal with the variation of RES production, system flexibility must be provided. System flexibility can be defined as "the general characteristic of the ability of the aggregated set of generators to respond to the variation and uncertainty in the net load" (Denholm & Hand, 2011, p. 1819). Verzijlbergh et al. (2017) distinguish four different mechanisms through which flexibility can be guaranteed. We will assess the extent to which these flexibility options are used in the energy systems in Denmark. All forms are therefore shortly discussed here. The first flexibility mechanism is flexibility from the supply side. This can be done through curtailment of power plants, meaning that production is temporarily limited or ramped down (Holttinen et al., 2016). Curtailment can be applied to conventional power plants as well as to RES. The second mechanism is energy storage. Various storage technologies with deviating characteristics, such as storage capacity, lifetime and response time, exist. Storage plays a key role in renewable based energy systems and is therefore considered as a crucial element. To assess the type of storage technologies used in the Danish electricity system, the article of Hadjipaschalis et al. (2009) has been used. They distinguish six different storage technologies that can be used to store electrical power. These options are as follows: flywheel storage technologies, battery storage technologies, supercapacitor storage technologies, hydrogen storage technologies, pneumatic storage technologies and pumped storage technologies. The third flexibility mechanisms is flexibility from the demand side: demand response and smart grids. Demand response (DR) is defined as "electricity demand that can be shifted in time to anticipate or react to certain signals" (Verzijlbergh et al., 2014, p. 5). Mostly these signals are financial. DR is a form of energy storage in which household applications such as refrigerators, electric vehicles or heat pumps are used as batteries. The last mechanism is interconnection of networks. National networks were originally built to connect different power systems for back-up and flexibility. Cross-border interconnection of networks can be used to connect electricity systems of various countries. Surplus RES generation can then be transported to other countries rather than being sold for low prices on the domestic energy market. The different flexibility options must be used alongside one another to effectively deal with the intermittent character of renewables. Assessment of the provided flexibility options is the first step in the energy security assessment.

The following variable concerns **strategic reserves.** Strategic reserves aim to create sufficient reserve capacity that can be used in exceptional situations when existing capacity cannot meet demand (Neuhoff et al., 2016). Scholten (2018) assumes that in a renewable energy system, largely influenced by intermittency, the emphasis shifts from having access to sufficient resources and strategic reserves, to grid balancing activities and storage. He uses the term strategic reserves specifically for stocks of fossil fuels. Neuhoff et al. (2016) on the other hand, use the term strategic reserves also for electrical power reserves. They refer to capacity that is sold at the spot market in times of exceptional scarcity. It is a time-limited, flexible initiative that helps to maintain generation adequacy (Energinet, 2018c). In both fossil fuel based and the wind energy systems, strategic reserves can be used to guarantee security of energy supply in exceptional circumstances (Neuhoff et al., 2016). We will therefore assess how strategic reserves are provided by both systems and how they affect energy security.

Dependency

In regard of dependency on foreign countries, two indicators are selected. First**, the share of imports of fossil fuels, electricity and materials.** The extent to which import dependency forms a problem for energy security depends on the magnitude of the import flow. If only a small part of the total use is imported, dependency is less tricky.

Next to the magnitude of the import flow, also the **nature of the relation between Denmark and the exporting country** influences energy security. If sources are, for example, imported from neighbouring countries with which Denmark has good relations, import dependency is considered less problematic. It is therefore important to assess the nature of the relations between countries.

Diversification

The first selected indicator concerning diversification is the diversification of **electricity generation mix.** In order to guarantee a stable flow of electricity, it is important that countries do not heavily depend on one source. Spreading risks by diversifying the generation mix can therefore increase energy security. If, for example, countries are largely import dependent since they do not possess a certain fuel, they can reduce this risk by diversifying their electricity generation mix. They then depend to a lesser extent on imports of a particular source.

Likewise, it is important for countries not to rely too heavily on specific suppliers or consumers for import or export streams. The second indicator therefore is **diversification of suppliers and consumers of fossil fuels, electricity and materials.** Different suppliers and consumers from various nations or regions increase energy security.

Furthermore, **diversification of generation and distribution companies** is important. The influence of single companies is reduced when the share of different companies is larger. This will not only lead to more competition on the market, it will also contribute to a market that is stable and secure.

Price stability

Next, we include the variables **electricity price stability** and the **electricity price level** compared to the European average**.** Affordability is an important aspect of energy security, which is often included in energy security indices (Ang et al., 2015). Price stability and electricity price levels are indicators included to assess whether price fluctuations are limited to a certain level and whether electricity stays affordable for households. Their effect on energy security is assumed to be the following. High price fluctuations can lead to unstable markets and hinder long term investments in energy infrastructure (Pascual & Zambetakis, 2017). Lack of investment in energy infrastructure might be a threat to energy security. Furthermore, looking into the electricity price level, end-users prefer low electricity prices since they can foster economic growth (Azzuni & Breyer, 2018). While low prices might therefore seem to have a positive effect on energy security, it is not as straightforward. Energy security largely depends on large-scale investments which are threatened by low electricity prices (Kisel et al., 2016). Electricity prices should hence neither be too high nor too low. In order to assess the electricity price fluctuations and levels in Denmark, we compare them to the average European values.

Innovation and research

The next selected variable is the **available knowledge on energy technologies.** As Criekemans (2018) states, the transition towards a renewable energy system enlarges the role of technology. Countries consisting of knowledge on renewable energy technologies can sell products and services in the industry to other countries, which leads to new energy relations. A possible way to assess the available knowledge in a country is by looking at the amount of patents awarded (Criekemans, 2018) or intellectual property on renewable energy technologies and R&D expenditures (IRENA, 2019; O'Sullivan et al., 2017). In this study, the indicator Revealed Technical Advantage (RTA) is used, which is the share of a country's patents in a specific energy technology divided by the total share of patents held by the country (Bonnet et al., 2019). This indicator gives insight into the relative specialization of a country in a technology. Countries that succeed in gaining knowledge on renewables and become industrial leaders in the field of renewable energy technologies are likely to benefit from that (Vakulchuk et al., 2020).

Safety and reliability

To generate a rough insight in the reliability of the system, we want to assess the **minutes of interruptions of electricity supply per person per year.** This number shows us whether reliability of the system has changed since the large-scale integration of wind energy.

As described earlier in the literature section, a system largely based on renewable energy sources might be more vulnerable for **cyber security threats**. We therefore aim to outline to what extent the number of cyber security attacks has changed and the extent to which Denmark sees this as a problem.

Resilience and adaptive capacity

The limited predictability and high variability of wind energy production induces challenges for the **operation of the electricity grid**. For example, voltage and frequency stability might be affected by an increasing share of wind energy in the system (Holttinen et al., 2016). A robust transmission grid needs inertia, short circuit power and voltage control. Ibrahim et al. (2011) explains it as follows: there are no technical constraints to the integration of wind power but as the share of wind power grows, measures must be taken to guarantee a reliable power grid.

Competition and markets

The next variable refers to the importance of the electricity sector to the Danish economy. The more important the sector is to the Danish economy, the more vulnerable the country if (export) flows are disrupted. Or in other words, the larger the sector, the more important for national security. The focus lies on the **generated revenues** due to the export of wind turbines or wind turbines components **as a share of GDP**.

The last selected variable concerns **the number of parties with decision rights on cross border flows.** Steinbacher et al. (2019) distinguishes two different ownership models used for cross-border electricity trade in Europe. The first is the regulated ownership model in which the Transmission System Operators (TSO's) are responsible for financing, building and operating cross border connections. The second one is the merchant ownership model. In this model, independent private investors, are the owners of the interconnectors. If the first model is applied, social welfare will be the major goal of the interconnectors and high revenues will be the aim of the second model is applied.

Policy considerations

The second part of the third step examines the policy considerations required to safeguard energy security. The underlying assumption of this step is the fact that countries attempt to safeguard their energy security. So, if we observe certain vulnerabilities or insecurities in the energy security situation of Denmark in 1990 or in 2018, it is likely that national energy policy is used to overcome or reduce these insecurities. The policy considerations discussed in this step are hence based on the findings of the energy security assessment. The following three variables are evaluated for both years:

- **Policy aims:** the final goal that implementation of the policy must achieve. For example, reducing import dependency on oil.
- **Policy strategies:** the way in which the goal must be achieved. For example, diversification of electricity generation mix, and increase domestic production.
- **Policy tools:** concrete measures that can be used in order to achieve the goal. For example, subsidies for biomass and investments in search for national oil fields.

Patterns of cooperation and conflict

The last part of this step evaluates the energy-related patterns of conflict and cooperation. We base our analysis on the identified energy policies in the previous step and on the energy relations identified in the energy security assessment. The aim of this section is to generate more insight into the type of conflict or cooperation that exists between two or more countries. Three variables are distinguished:

- **Nature:** the essence of the relation. For example, is the type of conflict diplomatic, legal-institutional, political, an economic pressure or sanction or a military intervention? And is the form of cooperation organized via long- or short-term contracts or via markets or bilateral?
- **Intensity:** the severity of the conflict and the amount of times that countries are trading. For example, countries are putting pressure on another nation to increase available transmission capacity versus through cyber-attacks countries try to cut off electricity in another nation. Or, countries are trading every day versus once a month.
- **Duration:** the time that the conflict or cooperation lasts. For example, countries are in war for 5 years. Or, a long-term contract on electricity trade was created for 25 years between Denmark and Germany.

2.2.4 Reflection on relationship

The last step of the framework involves a reflection of the relationship between the outcomes of the previous steps, taking broader contextual developments into account. The geopolitical implications of wind energy have been assessed in step three of the framework. The question is to what extent these geopolitical developments can be attributed to the specific characteristics of wind energy, or to what extent they are caused by external factors. There are, as Scholten (2018) points out many other case- or context specific factors that can shape interrelations between countries. He for example mentions climate change and local pollution, innovations in electricity storage and generation, globalization and economic growth, great power rivalry and historical interstate relations, national institutional arrangements, financial markets, increasing urbanization and public support. The aim of this section is hence to assess the extent to which the changes in interstate energy relations can be attributed to the technical and geographical characteristics of wind energy. We want to reflect on the relation between the dependent (interstate energy relations) and independent (technical and geographical characteristics) variable. Since this step is seen as a reflection on the previous findings, it will be discussed in a separate chapter. The chapter consists of two steps:

1. Comparison of the findings of the interstate energy relations in 1990 and 2018, and outlining the most important differences and similarities between the two situations.

2. Analysis of the differences in a geopolitical context. The goal is to outline other key developments that might have influences geopolitical relations between countries. Subsequently, we want to assess to what extent the changes can be attributed to the characteristics of wind or to other contextual developments.

2.3 Operationalization

In order to apply the adapted framework to the case of Denmark and measure the geopolitical implications of wind power, the main concepts need to be operationalized. Operationalization of all the concepts has been described in the earlier paragraphs. This section schematically summarizes the outcomes. The constructed framework that is applied in the following of this research is presented in Figure 4 below. This figure shows the relation between the four steps and the included components for each step. The arrow from step 1 to step 3 in Figure 4 illustrates the assessment of the relation between the independent variables in step 1[18] and the dependent variables in step 3.[19] Table 4 and 5 schematically outline the included variables for each component, and the concrete indicators used to measure these variables. As can be seen, the variables for the energy security component sometimes have more than

[18] Variables under source, generation and distribution.
[19] Variables under energy security, policy considerations and patterns of cooperation and conflict.

one indicator. Due to general, wide-ranging character of some these variables, various indicators are assumed to be relevant.

While a rationale for including each of the variables is provided in the previous sections, some of the most important ones are shortly described here. A summary of the rationales why variables of Scholten (2018) are left out, changed or new ones added can be found in Appendix E. Comparing the constructed framework to the framework as created by Scholten in Figure 2, one can see that two components (business models and welfare effects) in step 2 are left out. Since the main focus of this study is to examine the arising energy trade relations *between* countries, business models and welfare effects *within* countries are not taken into account. Furthermore, some variables specific for wind energy are added. For example, the size of the Danish coastal area is assumed to give insight into the offshore generation potential. The longer the coast line, the more options countries have to generate offshore wind power. To specify the framework to a concrete case and adopt a country specific perspective, the variable 'neighbouring countries' has been added. It is assumed that neighbouring countries are increasingly important in an electric system because trade options are limited. It is therefore important to understand the geographical context in which the system is embedded. The variable 'time constraints' entails whether storage is required and what possible storage markets exist. Since the variable 'storage means' was already incorporated in the first step. It is therefore assumed that including it once again might lead to overlapping information.

The constructed operationalization frameworks in Table 4 and 5 below are systematically applied to the Danish electricity system in 1990 and 2018 in the following chapter (chapter 3). Step 4, the assessment of the relation is analysed in chapter 4.

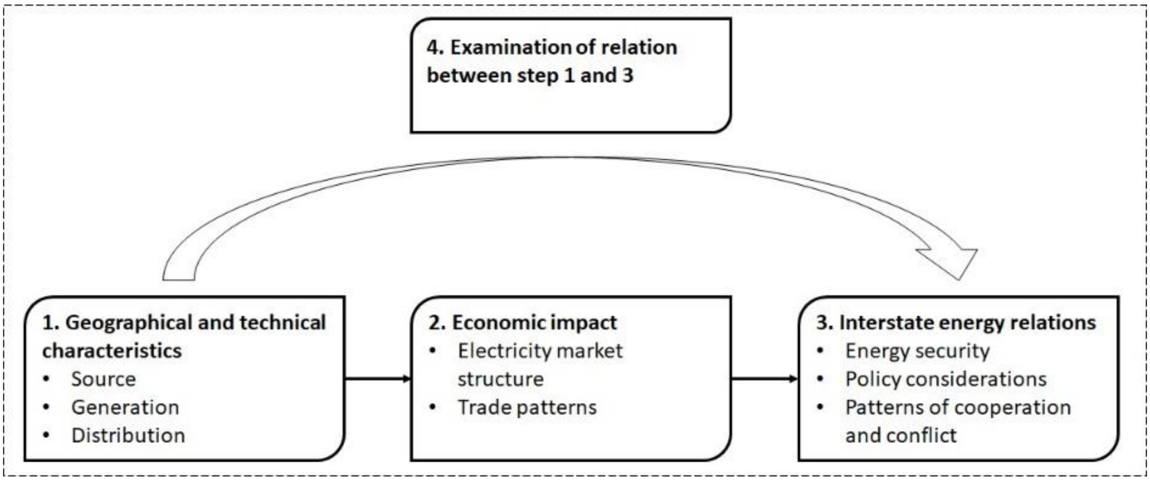

Figure 4. Constructed framework and included components. Source: adapted from Scholten (2018)

Table 4

Operationalization of geographical, technical and economic variables

Geographical, technical and economic dimensions, variables and indicators

Components	Variables	Indicators fossil fuel system	Indicators wind energy system
Source	Geographic location	Presence (Yes/No)	W/m^2
	Stability/Variability	Stable (Yes/No)	Stable (Yes/No)
	Generation potential	Reserve/production ratio and consumption/production ratio	MW/Capita
	Coastal area	-	Km
Generation	Technology and lifespan	Type of technology and years	Type of technology and years
	Central/Decentral nature	%	%
	Critical materials	Type of critical materials used	Type of critical materials used
Distribution	Network technology and topology	Nature of source and transportation means	Nature of source and transportation means
	Operating systems	Managerial requirements	Managerial requirements
	Storage means	Type of storage options used	Type of storage options used
	Neighbouring countries	Amount	Amount
	Vulnerabilities in the system	Type of vulnerability	Type of vulnerability
Electricity market structure	Market scope	Regional/Global	Regional/Global
	Number of producers and consumers	Single/Few/Many	Single/Few/Many
	Barriers to entry/exist	Low/medium/high	Low/medium/high
	Price stability	Annual % change	Annual % change
Trade patterns	Trade flows of materials or products	Trade partners and size of stream	Trade partners and size of stream
	Trade flows of energy sources or carriers	Size of flows (in GWh, 1000 tonnes and million m^3)	Size of flows (in GWh, 1000 tonnes and million m^3)
	Interconnectivity between countries	Installed capacity (MW/country)	Installed capacity (MW/country)

Table 5

Operationalization of interstate energy relations, policy considerations and patterns of cooperation and conflict. Source: adapted from Sovacool & Mukherjee (2011)

Interstate energy relations		
Components	**Variables**	**Indicators**
Energy security	Security of supply	Use of flexibility options
		Strategic reserves in type and MW
	Dependency	Share of imports of fossil fuels, electricity and materials
		Characteristics of relation between Denmark and exporting country
	Diversification	Diversification of electricity generation mix
		Diversification of suppliers and consumers of fossil fuels, electricity and materials
		Diversification in generation and distribution companies
	Price stability	Electricity price fluctuations per year
		Electricity price level compared to European average
	Innovation and research	Revealed Technical Advantage (RTA): Country's share of patents in a particular technology/ country's share in all patent fields
	Safety and reliability	Minutes of interruptions of electricity supply per year
		Cyber security threats
	Resilience and adaptive capacity	Operation of the electricity grid
	Competition and markets	Revenues from electricity sector as share of GDP
		Number of parties with decision rights on cross border trade
Policy considerations	Policy aims	Final goal that a certain policy must achieve as identified by the government
	Policy strategy	Manner to achieve the policy aim
	Policy tools	Available policy measures
Patterns of cooperation and conflict	Nature of pattern of cooperation or conflict	Characteristics of relations
	Intensity of pattern of cooperation or conflict	Severity of relations
	Duration of pattern of cooperation or conflict	Years of relations

3. The Danish electricity system in 1990 and 2018

The following chapter applies the constructed frameworks to the situation in Denmark in 1990 and 2018. In order to add context to both situations, the chapter starts with a brief history of the Danish electricity system before 1990. Section 3.2 outlines the geographical, technical and economic characteristics and the interstate energy relations of Denmark in 1990. Section 3.3 presents the major developments between 1990 and 2018. The chapter ends with application of the frameworks to the Danish situation in 2018: the geographical, technical, economic characteristics as well as the interstate energy relations are discussed.

3.1 A brief history

The history of wind energy in Denmark goes back several decades. In the 1970s, Denmark relied for more than 90 percent on foreign energy sources (Sovacool & Tambo, 2016). When the OPEC members announced an oil embargo during the oil crises in 1973 and 1979, the country's dependence on foreign oil became painfully obvious. Denmark's electricity generation was mainly based on oil from the Middle East by that time (Rüdiger, 2016). The oil embargo by Arab countries deeply affected the Danish economy and its citizens, and led to considerable economic difficulties. The widespread understanding of how problematic dependency on foreign, non-renewable energy sources could be, forced the government to enhance security of supply and stimulated an energy transition in the country (Ligtvoet & van Barneveld, 2016). Hence, in 1976 the government launched its first energy action plan, the Danish Energy Policy 1976. Main aim of the plan was to become more energy efficient and to reduce dependence on foreign oil by increasing the share of coal, nuclear energy and natural gas in the energy mix (IRENA-GWEC, 2013). Coal consumption increased quickly and in 1980, the coal consumption was already twice as large as oil consumption. Electricity companies also announced plans to construct nuclear energy plants (IRENA-GWEC, 2013). The Second Energy Plan, Energy Plan 81, was released in 1981. This plan focused on exploitation of domestic oil and natural gas in the North Sea (Rüdiger, 2016). Plans for nuclear power plants construction were placed on hold due to strong public opposition. In 1985, nuclear energy was officially off the table when a majority of Parliament decided to omit it from future energy plans (Rüdiger, 2019b). Nuclear energy has hence never been part of the Danish electricity mix. Power generators agreed to integrate 100 MW of wind energy into the system as an alternative for nuclear power (Gerdes, 2016). To support construction of these wind turbines, the Danish government created a grant program which could be used to cover 30 percent of the initial capital costs. From then on, wind turbines were gradually scaled up and started to become more and more important in the Danish energy mix. Figure 4 shows how wind power developed from 1990 onwards. The figure shows a stagnation of wind power capacity development between 2004 and 2008. This was mainly due to the liberalization of the electricity sector in 2003 and abundance of feed-in tariffs (IRENA-GWEC, 2013). A new energy agreement was published in 2008 in which the government announced the installation of two 200 MW offshore wind parks. Wind power capacity started growing again from then on.

Strong political support, stable policy, and excellent wind conditions have laid down a secure base to invest in wind energy. Wind has therefore successfully developed in the past decades. In 2019, wind energy accounted for 47 percent of the total power consumption and it is hence likely that Denmark will reach the target of 50 percent of wind in 2020. The share of wind energy is likely to increase even further the coming years since Denmark aims for a 100% renewable energy mix in 2050.

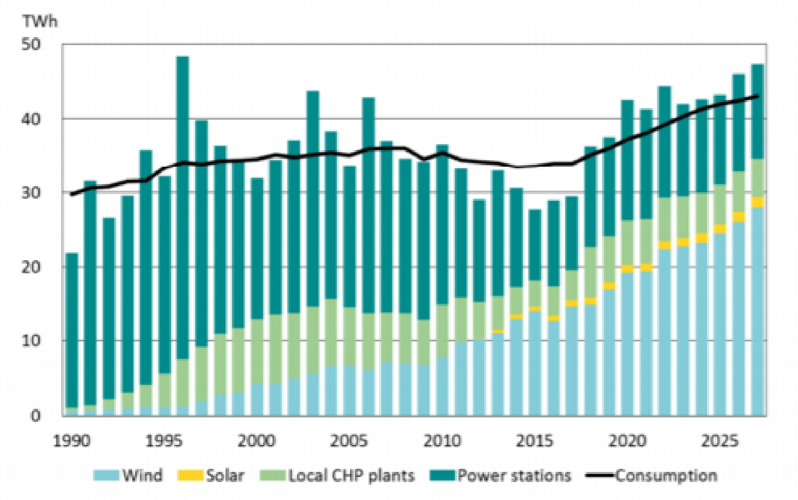

Figure 5. Electricity consumption and generation in Denmark from 1990 to 2027. Source: Energinet (2018)

3.2 The Danish electricity system in 1990

This section applied the constructed framework to the Danish electricity system in 1990. Step 1 is discussed in section 3.2.1, step 2 in section 3.2.2 and step 3 can be found in section 3.2.3.

3.2.1 Geographical and technical characteristics

Source

Geographic location

Figure 5 presents the cumulative electricity generation mix per source in 1990. As can be seen, the biggest share of electricity was produced by coal. Oil and natural gas were used as well, and a very small part of the electricity was already produced by wind energy and biofuels. Coal was not present in Denmark and was therefore imported from Australia, Colombia, the USA and Poland (Rüdiger, 2019b). Natural gas was already found in the Danish part of the North Sea in the 1970's. The Danish government therefore requested to increase exploration of these natural gas fields since this was the most appropriate manner to reduce dependence on foreign fuels. Domestic oil fields were discovered during that time as well. Oil and natural gas hence were present in Denmark while coal was not.

Stability/variability

As Figure 6 shows, coal was by far the most used energy carrier to generate electricity. Coal was complemented by natural gas and oil. The Danish electricity generation mix consisted thus for the largest part of stable energy sources in 1990.

Generation potential

In 1990, the consumption/production ratio of natural gas was 0,64, meaning that Denmark was exporting parts of its natural gas (BP, n.d.).[20] The reserve/production ratio was 30,3 years (BP, n.d.) The consumption/production ratio for oil was 1,6 and the reserve/production ratio was 14,7 years (BP, n.d.). Oil was thus mostly imported during that year. Three years later, in 1993, Denmark became self-sufficient for oil products as its export was larger than its import. Denmark did not have domestic coal, all the used coal was imported.

[20] The statistics obtained from BP are about the Danish natural gas and oil consumption and production in total and not just the amounts used for electricity production. This information was, unfortunately, not found. While the numbers should not be used to derive conclusions, they still give a rough insight into the energy trade patterns of Denmark.

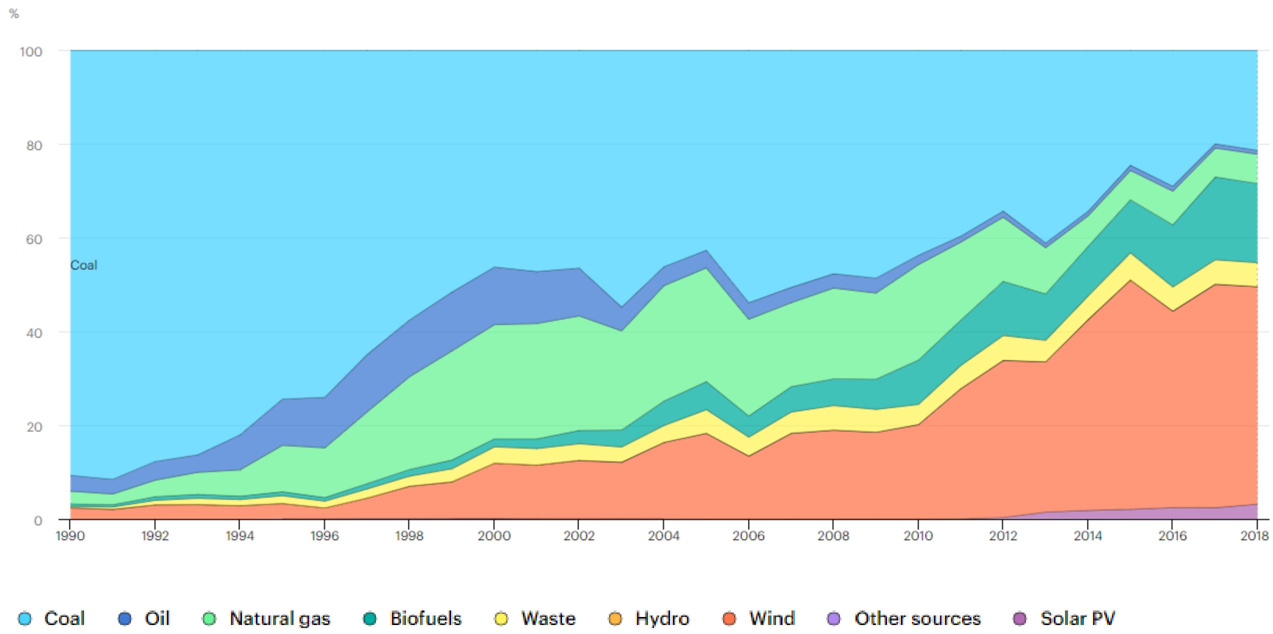

Figure 6. Cumulative electricity generation by source, Denmark 1990-2018. Source: International Energy Agency (2019)

Generation

Technology used

The technologies used to generate electricity were mostly large power plants, based on oil, coal of natural gas. Furthermore, Combined Heat and Power (CHP) plants were used to generate electricity and heat for district heating. The lifespan of these power plants was around 40 years.

Central/Decentral nature

Around 91 percent of the electricity was generated by large, central power plants complemented with a small share, around 8 percent of decentralized power plants (Danish Energy Agency, 2016). Most of the decentralized power plants were CHP plants, complemented with a small number of wind turbines. Power plants were owned by municipalities and consumers (Hvelplund & Djørup, 2020). Around 1990, a development started in which the amount of decentral CHP plants was increased. Figure 7 shows the development from a largely centralized to a more decentralized electricity system in Denmark between 1985 and 2015.

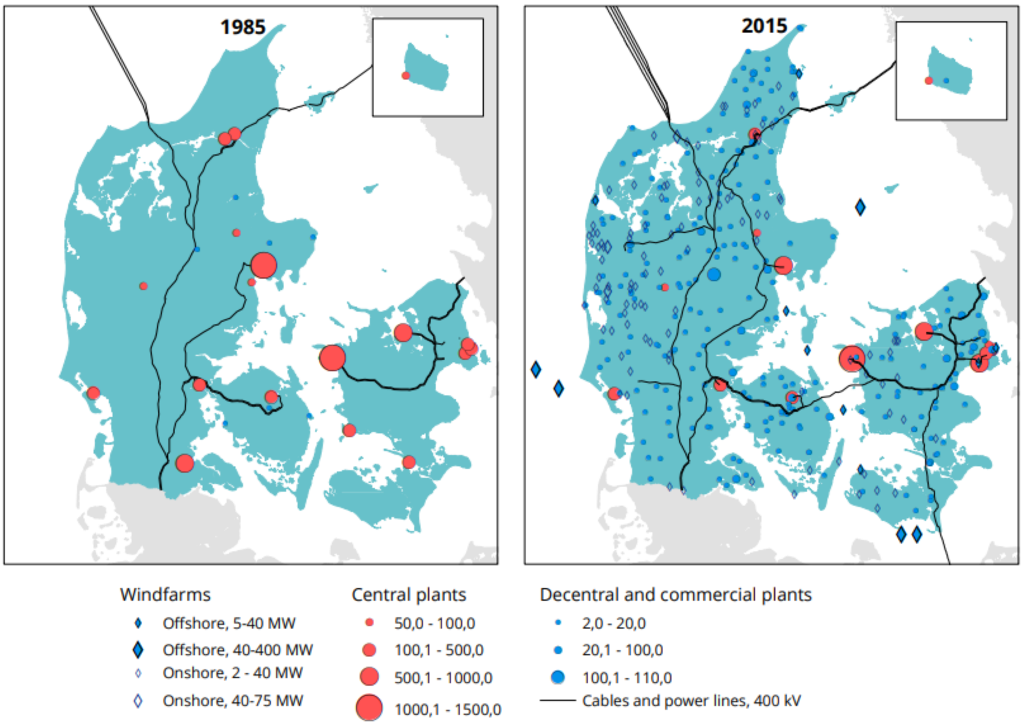

Figure 7. From centralized to decentralized power in Denmark. Source: Danish Energy Agency (2017)

Critical materials

The used energy generation technologies were conventional gas, coal or oil power plants, CHP plants and a small share of wind turbines. According to the list of European Commission (2010), no critical materials were needed to construct these power plants.

Distribution

Network technology and topology

The nature of coal, oil and gas were respectively solid, liquid and gaseous. Transportation of these sources could be done through pipelines, overseas or in trucks over roads or over rails. Once the power plants transformed these fuels into electricity, electricity was transported from the power plants to consumers through transmission wires. Hence, the system consisted of trucks, boats and trains, large power plants and electricity wires.

Operating systems

Already in 1990, grid planning was important in the Danish electricity system. Since the share of decentral CHP power plants was increasing, the electricity grid needed to be adapted as well. Adequate planning was therein crucial.

Storage means

Most of the Danish oil was stored in subsea storage tanks, from which the oil was pumped on board tankers. Natural gas was stored at natural gas storage facilities operated by DONG Naturgas A/S (The Danish Energy Agency, 2000). Furthermore, Denmark has stocks of imported coal.

Neighbouring countries

Denmark has two direct neighbours, Sweden and Germany. Norway and Denmark do not directly link to each other since they are separated by the North Sea. The two countries are however relatively close to each other. Denmark's electricity network was connected to the Swedish, German and Norwegian network in 1990.

Vulnerabilities in the system

Two out of three vulnerabilities, as distinguished by Månsson (2015), are relevant for the Danish electricity system in 1990. First, the system has parts of high energy density that might become targets of attacks. These energy dense parts are oil and natural gas fields and storage facilities. Second, the system is vulnerable to the failure of components. Since the system is largely powered by a few big power plants, failure of one of these plants has large consequences for electricity production.

3.2.2 Economic impacts

Electricity market structure

Market scope

As described, the market scope of electricity is in this study assumed to be limited to the physical network. Since Denmark had connections to Sweden, Norway and Germany, the scope of the market was limited to these 3 countries and Denmark itself. While electricity was traded on a regional level, oil, gas and coal were traded globally. Coal, came from Australia, the United States of America, Colombia and Canada. Oil was imported from Kuwait, Norway, Saudi Arabia and United States of America. The market scope was thus mainly organized on a global level.

Number of producers and consumers

The Danish electricity system consisted of two areas in 1990: West Denmark (DK1) and East Denmark (DK2) (Ocana, Siclen, Phillips, & Varley, 1999). These areas were not connected to each other so Denmark had two separate transmission grids. Each of the areas were dominated by a vertically integrated energy organisation: Elsam in western Denmark, and Elkraft in eastern Denmark. Elsam operated six central energy production companies and Elkraft controlled two generating companies. The number of producers was thus low. The two companies controlled generation, owned the transmission network and owned the links to foreign countries (Swedish Energy National Administration, 2000). Since Elsam and Elkraft had the centralised control of generation rather than the individual generating companies, they were considered as the strategic players in the Danish electricity sector (Ocana et al., 1999). The number of consumers was large and consisted of various players such as households, industries, transport and commercial and publication services (International Energy Agency, 2019).

Barriers to entry or exit the market

Since the market was operated by two vertically integrated parties, Elsam and Elkraft, it was difficult to enter the market for new parties outside these organizations. Barriers to entry were hence high.

Price stability

The electricity price per kWh for households including all taxes was 14,78 eurocents in 1995.[21] The European average was 13,53 eurocents and prices in Denmark were the fourth highest in Europe (European Commission, 2011). The electricity price without tax was 6,08 eurocents while the European average was 11,02. Denmark had thus very high electricity taxes. Between 1995 and 2000, the Danish electricity price (including taxes) increased with 32 percent to 19.66 cents per kWh, while the average European price decreased with 2 percent. Denmark has had one of the highest electricity prices in Europe during 2000 and 2005 as well. Increases of the electricity price were however quite gradually spread over the years.

Trade patterns

Trade flows materials or products

For the construction of fossil fuel-based power plants, no critical materials were required. There are therefore no critical material trade flows identified. Furthermore, information on trade flows of materials and components needed for the construction of power plants was not found. They are therefore

[21] Data on electricity prices before 1995 was not found so data from 1995 is used in this section.

not included. Already before 1990, Danish engineers were interested in wind power. In 1976, the first wind turbine emerged in the Danish landscape and the company Vestas started to produce wind turbines. By then, Denmark was exporting wind turbines to California (van Est, 1999).

Trade flows of energy sources or carriers

Electricity was traded with Norway, Sweden and Germany in 1990. In total, 11973 GWh of electricity was imported and 4925 GWh was exported. A more detailed overview of the exact import and export values per country are presented in Figure 8.

Most electricity was produced from coal, which was imported from nine different countries. The United States of America, Colombia, Australia and Canada were the largest coal suppliers. The total import was 8765000 tonnes of coal (Danish Energy Agency, 2018). Oil was imported from Kuwait, Norway, Saudi Arabia and United States of America. The total imports were 4112000 tonnes and total export 2769000 tonnes. Lastly, 1051 million m^3 natural gas was exported to Germany and Sweden.

Interconnectivity between countries

As pointed out earlier, Denmark was interconnected to Sweden, Norway and Germany. The total transmission capacity between Denmark and Norway was 550 MW. Between Denmark and Sweden interconnector capacity was divided over different transmission lines, in total 1670 MW (NORDEL, 1991). The exact trade capacity between Denmark and Germany was not found. It is, however, certain that both countries were connected.

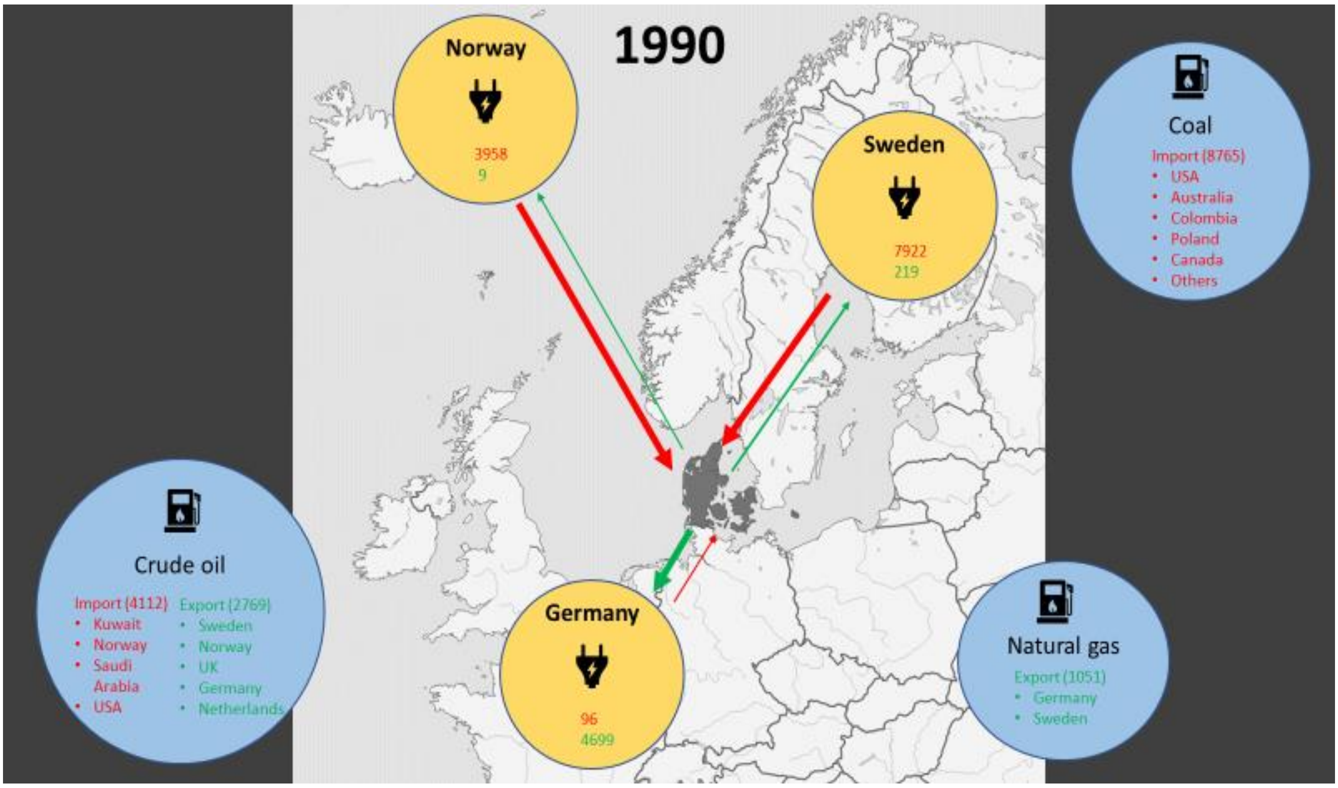

Figure 8. Import and export flows of Denmark in 1990. Electricity streams are in GWh, coal and oil in 1000 tonnes and natural gas in million m^3. Based on information from Danish Energy Agency (2018)

3.2.3 Interstate energy relations

The following section outlines the interstate energy relations in 1990. This is done by application of the energy security framework as constructed in the previous chapter. After, the policy considerations and patterns of cooperation and conflict are discussed.

Energy security

Security of supply

In the electricity system in 1990, **flexibility** was provided on the supply side by ramping up and down thermal power plants. Since almost no intermittent sources were penetrated in the system, production was stable and flexibility was limitedly needed.

No information on **strategic reserves** in 1990 was found. Denmark could store coal, natural gas and oil to always have a stock of those fuels. We do however not have insight in how Denmark organized security of supply in times of power plant failures.

Dependency

The Danish electricity production was largely based on coal in 1990. Since Denmark did not poses domestic coal, Denmark was for 100 percent **import dependent** for its coal supply. Furthermore, around 56% of the used oil needed to be imported as well. Since only a very small part (3%) of electricity was produced by oil, import dependency of oil was not considered as a challenge to secure electricity supply. Natural gas was produced domestically and not imported. Concerning electricity import dependency, 39% of the electricity consumption was imported and 16% of the Danish electricity production was exported (International Energy Agency, 2019).

Relations between Denmark and the exporting countries do not have particular **characteristics** that are worth mentioning. In choosing the countries to import this coal form, Denmark focused on a fair price and good quality. Furthermore, the political situation of the supplying country was important. Denmark, for example, used to import coal from South-Africa before 1990 but due to the apartheids regime, Denmark halted import from this nation (Rüdiger, 2019b). Denmark traded electricity with its neighbouring countries, which are trusted by Denmark.

Diversification

The **electricity generation mix** was not **diversified** in 1990. 91% of electricity was produced from coal. Oil and natural gas both accounted for three percent, wind for 2% and biofuels for 1% (International Energy Agency, 2019). [22] Hence, electricity generation depended extremely on coal.

Denmark had learned from the oil crisis in 1973 not to rely on a single country and had therefore introduced a clear diversification strategy concerning import countries (Rüdiger, 2019b). This strategy resulted in a **diversified mix of** nine different **suppliers** of coal. The United States of America was their largest supplier and accounted for 37% of the total supply, Colombia for 23%, Australia for 13% and Poland for 11% and other countries for 16%. The negative impact of import dependency was hence diminished by the large number of different suppliers. Furthermore, we saw that Denmark imported a substantial part of its electricity from Sweden and Norway and exported to Germany. These trade patterns were seen as a way to generate revenues. Denmark could import cheap electricity from the Nordics and sell it for a higher price to Germany. The import dependency was hence not assumed to be problematic for the Danish energy security.

Concerning export of wind turbine materials, data shows that Denmark already started exporting wind turbines to California before 1986 (IRENA-GWEC, 2013; Kamp, 2002). Due to an expiration of subsidies and many technical problems, export to California came to halt in 1988. Furthermore, trust in wind turbines in Denmark decreased which in the end led to the bankruptcy of several Danish

[22] These percentages are based on generation within Denmark. Imported electricity has not been included.

manufacturers. Some of these manufacturers were able to make a new start in the early '90s in which they could build on their acquired knowledge and experience. Manufacturers learned to focus on more than one export country to reduce the risk of diminishing demand. This was an essential learned lesson for manufacturers to safeguard demand. After 1990, wind turbines were therefore exported to several countries, among which Germany, Spain were the biggest but also to California, India and China (Kamp, 2002).

Diversification of ownership of generation and distribution companies was low. As described under market structure, two vertically integrated companies, Elsam and Elkraft, operated the market (Slingerland, 1999). The small number of players was threatening fair competition on the market.

Price stability

Between 1995 and 2000, the Danish electricity price (including taxes) increased with 32% to 19.66 cents per kWh, while the average European price decreased with 2%. Between 2000 and 2005, Denmark had one of the highest electricity prices in Europe as well. **Price fluctuations** were, however, quite gradually spread over the years. They are therefore not considered to be a significant threat to energy security.

Relative price levels of electricity including taxes were high in Denmark **compared to other European countries**.[23] The price for one kWh, for households including all taxes was 14,78 eurocents in 1995, while the European average was 13,53 eurocents. Prices in Denmark were the fourth highest in Europe (European Commission, 2011). The price for electricity without tax was however far below the European average, namely 6,08, while the European price was 11,02 eurocents. Taxes on electricity in Denmark were thus high.

Innovation and research

Danish companies already developed expertise in the wind energy sector and construction of wind turbines before 1990 (van Est, 1999). Due to increased competition and technological developments, the sector was gaining knowledge and experience. The country's **RTA** was around 0,85 between 1992 and 2003, meaning that Denmark was largely specialized in the wind energy sector compared to other countries and compared to other industries in Denmark. It should be mentioned, however, that small countries have high RTAs relatively easy because they only focus on a limited amount of technology sectors (Bonnet et al., 2019). The small size of Denmark thus explains its high RTA of 0,85. Still, the high number represents the country's relative expertise in the sector, already in 1990.

Safety and reliability

Interruptions in electricity supply were on average 28 minutes per consumer in 1990 (Danish Energy Agency, 2015).

Since most of the electricity was produced by a small amount of large power plants, cyber-attacks could have had severe impact. There have not been any cyber threats or attacks at the Danish system around 1990 however.

Resilience and adaptive capacity

Thermal power plants are able to deliver the services that are needed to protect the transmission system from black-outs (Energinet & DEA, 2018). Additional **operations of the electricity grid** were therefore very limited in the system of 1990. Grid operations did thus not form a threat for energy security.

Competition and markets

No concrete numbers on the **revenues from the electricity market** in 1990 were found.

[23] This information is based on electricity prices in 1995, since electricity prices in 1990 were not found.

Two parties, Elsam and Elkraft, were having **decisions rights on cross-border flows**. In western Denmark, Elsam controlled the Danish share of the links to Sweden and Norway. In eastern Denmark, Elkraft owned the Danish parts of the connections to Germany and Sweden (Ocana et al., 1999). Sweden, Norway and Germany were having decision rights on their own part of the interconnectors. Since the interconnectors are partly owned by Danish parties and partly by foreign parties, decision rights were shared and some important decisions need to be made together.

Policy considerations

Identified insecurities of the electricity system have forced the Danish government to come up with certain policy aims and measures. Two identified policy aims in 1990 concern the reduction of import dependency on coal and the specialization in (components of) wind turbines. The following section discusses the employed strategy and used tools for both policy goals.

Reduction of import dependency on coal

The most important aim was to reduce the import dependency on coal. The employed strategy in order to achieve this was twofold. Denmark tried to support and facilitate the use of national energy sources, and it aimed to diversify its electricity mix (Rüdiger, 2019a). Increasing the use of national energy sources and diversification of the electricity mix was done by expanding the search for domestic oil and gas fields. Additionally, a state-owned pipeline was constructed so that the Danish oil fields were connected to the mainland (Rüdiger, 2019b). Furthermore, Denmark started to increase wind energy generation due to beneficial Danish wind conditions in the country. These wind projects received refunds, payed from the energy and carbon taxes (IRENA-GWEC, 2013).

Specialization in (components of) wind turbines

Wind power gained national interest in 1990 for two reasons. First, after the publication of the Brundtland report in 1987, the concept of energy security changed. The focus was no longer only on security of supply, but the environment and emission reductions were considered as well (Rüdiger, 2019b). Wind power was seen as environmentally beneficial option. Second, Denmark’s high RTA of 0,85 reveals the skills that Denmark already gained in the wind power sector in 1990. The obtained knowledge and experience in the industry were seen as a business opportunity for Denmark that could create jobs and be used as export product. The strategy was therefore to further specialize into wind power and increase knowledge and experience in this sector. The employed strategy was by setting a concrete, long-term target for wind energy penetration: 10 percent of the Danish electricity consumption needed to be supplied by wind energy in 2005 (IRENA-GWEC, 2013). This concrete target created trust among researchers and businesses to invest in the sector. Tools used to employ the strategy were refunds for wind projects, payed from energy and carbon taxes. Furthermore, a feed-in tariff was introduced that was set at 85% of the utility production and distribution costs (Meyer, 2004).

Patterns of cooperation and conflict

This section describes the nature, intensity and duration of the patterns of conflict and cooperation that Denmark had with other countries.

Cooperation

In 1990, Denmark was trading electricity with other Northern European countries, i.e. Sweden, Norway and Germany. Since there was no common electricity exchange market, electricity was traded via bilateral contracts between countries (Peter Markussen, personal communication, 23 July). These contracts lasted for a long time. The Konti Skan interconnector was the first from Western Denmark to Sweden, and was constructed in 1965. The intensity of the electricity trade was quite high. Morten Pindstrup (personal communication, 29 July) describes how electricity was changing flow direction twice a day from Germany to Denmark to Norway and the other way around. Electricity was thus traded on a daily basis in 1990.

Conflict

No energy related conflicts between Denmark and other countries are identified in 1990.

3.3 Key developments between 1990 and 2018

Structural reforms took place in the Danish electricity sector between 1990 and 2018. The most important developments in the sector, and major contextual changes, are discussed in the following section. The developments are summarized in Figure 9. Outlining these developments supports the assessment of the relation between the changes in interstate energy relations and characteristics of wind power in step 4.

First, Sweden, Finland and Austria joined the European Union in 1995. Their membership meant that from then on, the same European rules applied to these countries as to Denmark. European membership has also consequences for other issues such as free trade of goods or European cooperation mechanisms.

A joint Swedish-Norwegian power exchange market, called Nord Pool ASA, was established in 1996. Finland joined in 1998 and in 2000, when Denmark also joined Nord Pool ASA the Nordic market was fully integrated. Through this common market, competition was added to the market and electricity could be freely traded between the different countries. Such an integrated market can enhance productivity and increase efficiency of the market. Over the years, new countries have been added the power exchange market. At the moment, 14 different nations are trading electricity through the Nord Pool market. Furthermore, Nord Pool offers additional related services such as compliance, data and sources. The formation of such a market is assumed to be a key-enabler for cost-efficient integration of variable renewable energy sources such as wind power (Energinet & DEA, 2018).

Liberalization of the Danish electricity market took place in 2003. The EU has been trying to liberalize electricity markets from early 1990 onwards. In 1996, the first liberalization directive (First Energy Package) was adopted by the Member States of the European Union. The main aim of this directive was to open national electricity markets and to increase competition and have lower electricity prices for consumers. Various countries liberalized their market in different years. Liberalization of the Danish electricity market in 2003 meant that consumers were free to choose their suppliers from then on.

The Danish TSO, Energinet, was created in 2005. Energinet is a merger of the grid operators Eltra, Elkraft SYSTEM and Elkraft Transmission and the natural gas transmission operator Gastra. Energinet owns, operates and develops the power and gas transmission systems. The company is a fully state-owned organisation, in hands of the Ministry of Climate and Energy. Instead of two different TSOs for the eastern and westerns part, Denmark had from 2005 onwards, only one national TSO.

The United Nations Climate Change Conference was organized in Copenhagen in 2009. Hosting this important climate conference was an important moment for the Danish government and companies and had a significant impact on the way in which they tackled climate change. The conference also led to a revival of the wind power market (IRENA-GWEC, 2013).

The eastern and western electricity systems of Denmark were connected to each other by the Great Belt Power Link, in 2010. The main aim of the link was to improve the utilization of Denmark's transmission resources and generation capacity. Furthermore, the link increases energy trading and general performance of the Nordic electricity market.

In December 2015, the Paris Agreement was signed during the COP21. This agreement brings together all nations to take action to fight against climate change and adapt to its effects. The major aim of the agreement is to strengthen global response to combat global warming and keep temperature rise below 1,5 degree. Signing of the agreement has been an important moment in history.

Another major development between 1990 and 2018 that is less related to the energy sector is digitization. Almost every sector has been affected by digitization and has faced structural reforms.

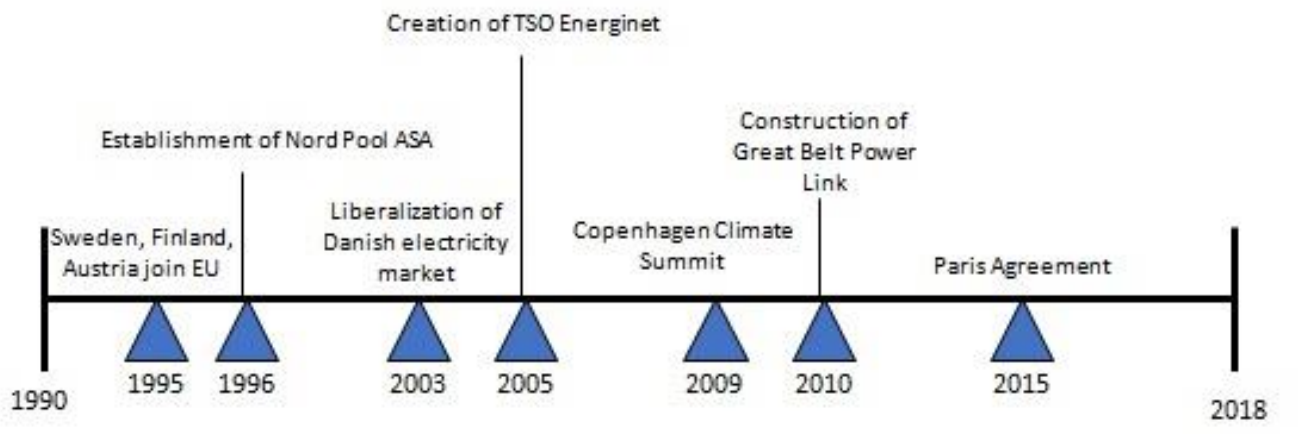

Figure 9. Major developments between 1990 and 2018

3.4 The Danish electricity system in 2018

3.4.1 Geographical and technical characteristics

Source

Geographic location

Wind energy density is Denmark is 650 W/m^2 at a height of 100 meter, measured at the 50 percent of windiest areas (Global Wind Atlas, 2019). This relatively high wind density makes Denmark a suitable country to deploy wind energy. [24]

Stable versus variable characteristics

Figure 6 shows that wind energy has been the most important energy source for electricity production in 2018. Wind has an intermittent character and hence, electricity production by wind energy is variable. The electricity mix is complemented with stable sources, of which coal and biofuels were the most significant. Natural gas, oil and waste were used as well.

Generation potential

The generation potential provides insight into the available onshore land that can be used to deploy wind energy. Denmark is a relatively small country with an above average population density. Its generation potential for onshore wind is therefore relatively low, i.e. lower than 1,2 MW/km^2 (Enevoldsen et al., 2019).[25]

Coastal area

Wind energy can not only be deployed onshore but offshore as well. It is therefore important for wind energy systems to assess the coastal area and size of the sea. The Danish coastline is 7314 km and the Danish sea comprises 660 km^2 (CIA Factbook, 2020).

Generation

Technology used

Wind turbines are used to produce electricity from wind power. The average lifetime of these turbines is 25 years.

Central versus decentral character

Around 20 percent of generation was centralised and 80 percent of the generation was decentralised in 2016 (Danish Energy Agency, 2016).[26] There were around 100.000 small- and large-scale electricity generation plants in Denmark (Energinet, 2016). Figure 7 shows the increased share of decentrally generated electricity in 2015 as compared to 1985. According to Poul Erik Morthorst (personal communication, 3 July), the system is shifting back to a central system again. The small scale, decentral wind turbines are being replaced or becoming less important. The biggest share of electricity is generated by large offshore wind parks that are operated centrally. Energinet (2018b) also reports on the rising trend of electricity that is not consumed where it is produced.

Critical materials

Construction of certain components of wind turbines requires critical materials. The identified materials fall under the rare earths group, and are as follows: dysprosium, neodymium and praseodymium (SETIS, 2015).

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[24] Mean wind power density is measured on a scale between 25 and 1300 W/m^2 by the Global Wind Atlas (2019)
[25] Generation potential in MW/km^2 varies between lower than 1.2 or higher than 6.2.
[26] Statistics for the year 2016 have been used here. This was done because then the same information source for the year 1990 and 2016 could be used to limit the different measurement methods.

Distribution

Network technology and topology

Electricity has an electric nature, so transmission lines are used to transport electricity from the location of production to the location of consumption. The system consists of wind turbines, converters and the electricity grid.

Operating systems

A system largely based on variable electricity generation necessitates more stringent operating requirements. Two major mechanisms are identified. First, reinforcement of the electricity grid and adequate grid planning. The increased share of wind power penetration requires a stronger grid at specific locations. Since construction of new wind turbines is done much faster than grid enforcement, adequate planning is crucial. Second, Denmark created a Datahub: a central IT-system which enables communication and standardisation processes to handle interaction between the different players in the electricity market (Energinet, 2016). The Datahub aims to stimulate competition and optimize market conditions for customers. Furthermore, Datahub paves the way for prosumers (consumers that are both producer and consumer of electricity), so that they can sell their electricity to the grid. This is important in a decentral system wherein consumers can own and operate wind turbines as well.

Storage means

Electricity is not yet stored on a large-scale in Denmark. Electricity storage in batteries is for example barely used because it is too expensive and not economically efficient (Poul Erik Morthorst, personal communication, 3 July).

Neighbouring countries

Denmark's direct neighbours are Sweden and Germany. Norway and Denmark do not directly link to each other, they are separated by the North Sea. The two countries are, however, relatively close to each other. Denmark's electricity network was connected to the Swedish, German and Norwegian network in 2018.

Vulnerabilities in the system

The most important vulnerability of the wind energy system is the fact that the system relies on complex electricity control systems, which can become target of cyberattacks. An example is the previously described Datahub in which a lot of sensitive data is shared. According to Thomas Egebo (personal communication, 4 August), cyber security is becoming a bigger threat for almost all sectors but if one would make a top ten with the most affected industries, the energy sector would be definitely on it. Cyber security is hence a growing focus for the energy sector.

3.4.2 Economic impacts

Electricity market structure

Market scope

The market scope has not changed compared to 1990, in that it still consists of Denmark itself, Norway, Sweden and Germany. Size of the market has slightly grown, in 2016, the total electricity consumption was 32004 GWh (as compared to 28862 GWh in 1990) (Danish Energy Agency, 2018).

Number of producers and consumers

The number of producers has increased compared to 1990. While the large electricity generation companies still exist, more electricity is generated by small scale parties as well. It has become easier for these kind of parties to generate and sell electricity. Hence, both the number of producers and consumers were high in the electricity system of 2018.

Barriers to entry or exit

Since the liberalisation of the power sector in 2003, complexity has been added to the sector, and the number of involved organisations increased. The main aim of liberalisation was to lower the barriers to enter the market so that competition was added to the market. The liberalization of the Danish retail electricity market increased competition and enabled consumers to freely choose their electricity supplier. The Danish TSO is even forced by law to add to the best possible conditions for competition with its activitites (Energi- Forsynigs- og Klimaministeriet, 2018). Barriers to entry and exit the market were thus low in the electricity system of 2018.

Price stability

Electricity prices in Denmark were the highest in Europe in 2018. The average price for one kWh electricity for households was 31,2 eurocents (EUROSTAT, 2019a). This high electricity price can mainly be explained by the high taxes on electricity, i.e. the share of taxes and levies was 64 percent in Denmark. Dong et al. (2019) found that wind has some influence on the volatility of electricity prices. They compared electricity prices in Sweden and Denmark and found that Swedish prices were more stable because it largely depends on more stable hydropower sources. They found, however, that in western Denmark the prices were not necessarily more volatile. The price volatility stays relatively low there, probably because there is very high percentage of wind power used there, which can often cover most of the demand. While we did not find data to specifically describe annual change of electricity prices, we conclude that the increasing share of wind power has affected price volatility in Denmark, as found by Dong et al. (2019).

Trade patterns

Trade flows materials or products

Denmark was exporting (components of) wind turbines to several different countries in 2018. Danish was mainly exporting wind turbine components to the United Kingdom, Germany, the United States of America (Vindmølleindustrien, 2018). Denmark was also importing several components of wind turbines. We could unfortunately not find concrete data on wind turbine imports. We can give a rough estimation however. Figure 10 below shows the locations of manufacturing facilities through Europe. Most companies do not only locate their manufacturing in the country where the headquarters are located by also where they supply wind turbines and components (Magana, Shortall, Telsnig, Uihlein, & Hernández, 2017). This can be partly explained by the fact that some of the wind turbine components are not very suitable for long-distance transportation because of their form and weight. As can be seen in the figure, most of the companies are located in Denmark, Germany and Spain. The EU as a whole leads the wind power sector but there are also many wind turbine companies located in the United States, China and India. While we did not find exact data on the countries that Denmark is importing from, we assume that they trade with countries having the highest share of wind turbine companies. Thus Germany, Spain, United States of America, China and India.

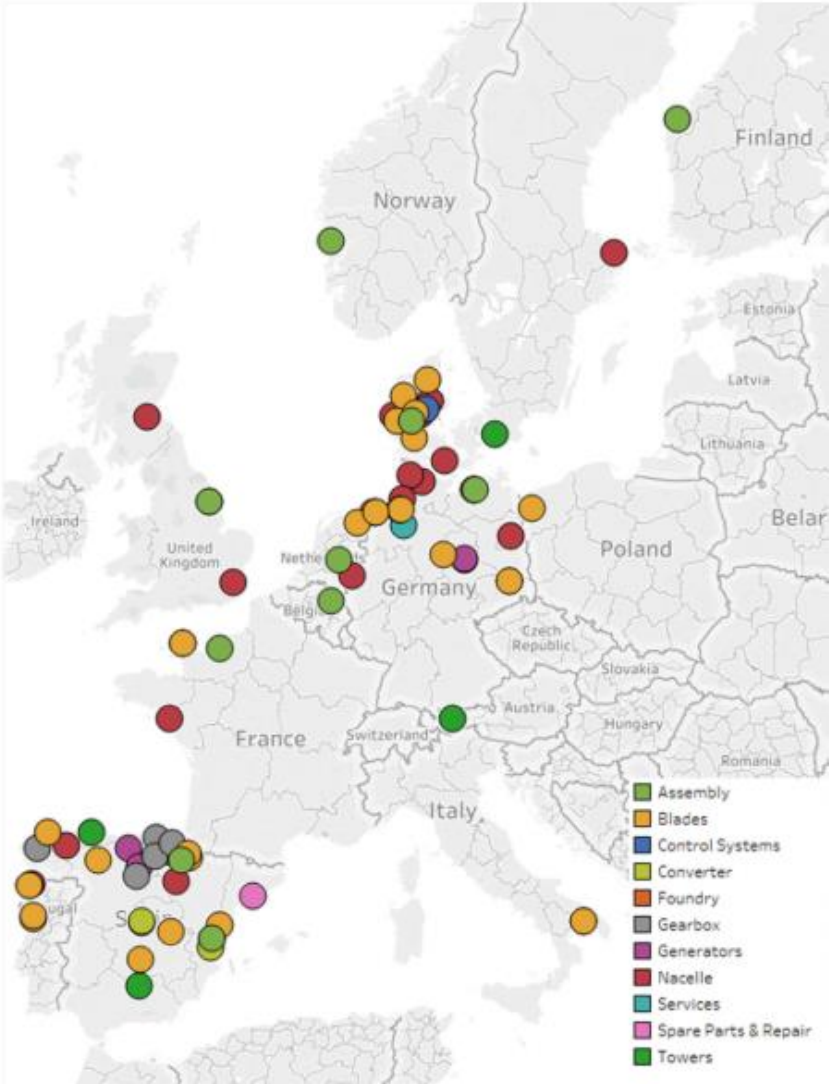

Figure 10. Manufacturing facilities of wind turbine components in Europe. Source: Magana et al. (2017)

Trade flows of energy sources or carriers

Electricity was still traded with Sweden, Norway and Germany. Denmark was a net-importer of electricity in 2016 and as can be seen in Figure 11, it has been a net-importer over the last several years. [27] The export peaks in 1996, 2003 and 2006 were due to dry years that resulted in low water levels in Norway and Sweden (Energinet, 2018). These low water levels induced high electricity market prices, making it beneficial for Denmark to export. The graph also shows that electricity trade has increased compared to 1990 but that the exact trade levels vary greatly per year. In 2016, Denmark imported 14976 GWh of electricity and exported 9919 GWh. The exact electricity flows per country are presented in Figure 12.

Next to electricity, Denmark also imported and exported fossil fuels in 2016.[28] After the 47 percent produced by wind, most electricity is produced from coal, which is mainly coming from Russia, South-Africa and Colombia. Natural gas is traded with the Netherlands, Norway, Germany and Sweden.

[27] Data for this section is provided by the Danish Energy Agency (2018). Since data from 2018 is not yet published, we base our analysis on the data from 2016.

[28] Biofuels (biomass and biogas) have increased significantly in the Danish power mix as well. Most of these biofuels are imported. Since the main focus of this study is to assess the shifting interstate relations as induced by wind energy, biofuels are not included in this study.

Oil is imported from seven different countries of which Norway is the biggest. Export of oil is also spread over different countries. Sweden is the largest importer of Danish oil.

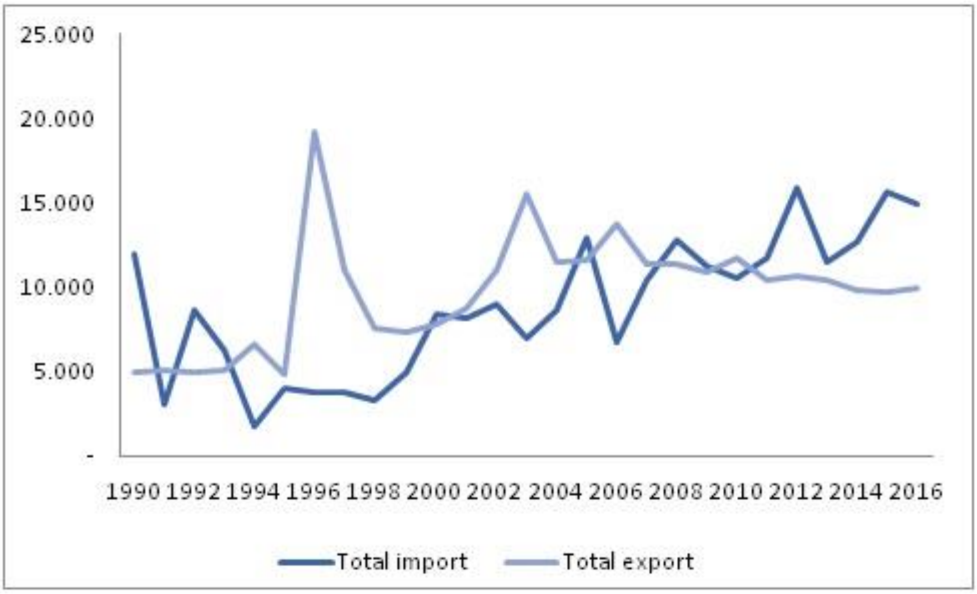

Figure 11. Cumulative import and export of electricity in Denmark between 1990 and 2016. Based on data from Danish Energy Agency (2018)

Interconnectivity between countries

Compared to the level of 1990, the overall trade capacity of electricity between Denmark and its neighbouring countries has increased. Trade capacity with Norway increased from 550 MW to 1632 MW. Capacity with Sweden also increased from 1670 to 2415 MW and trade capacity between Denmark and Germany was 2380 MW in 2018 (ENTSO-E, 2020). Furthermore, construction of the cobra cable started in 2018. This cable connects the Danish and the Dutch grid and allows the countries to trade electricity from 2019 onwards. However, new challenges concerning available capacity arose as well. The transmission capacity with Sweden temporarily reduced due to grid congestion at the West Coast Corridor in Sweden (Danish Utility Regulator, 2019). The Swedish TSO has therefore announced to take measures to reduce the impact of congestion on the interconnections between Sweden and Denmark.

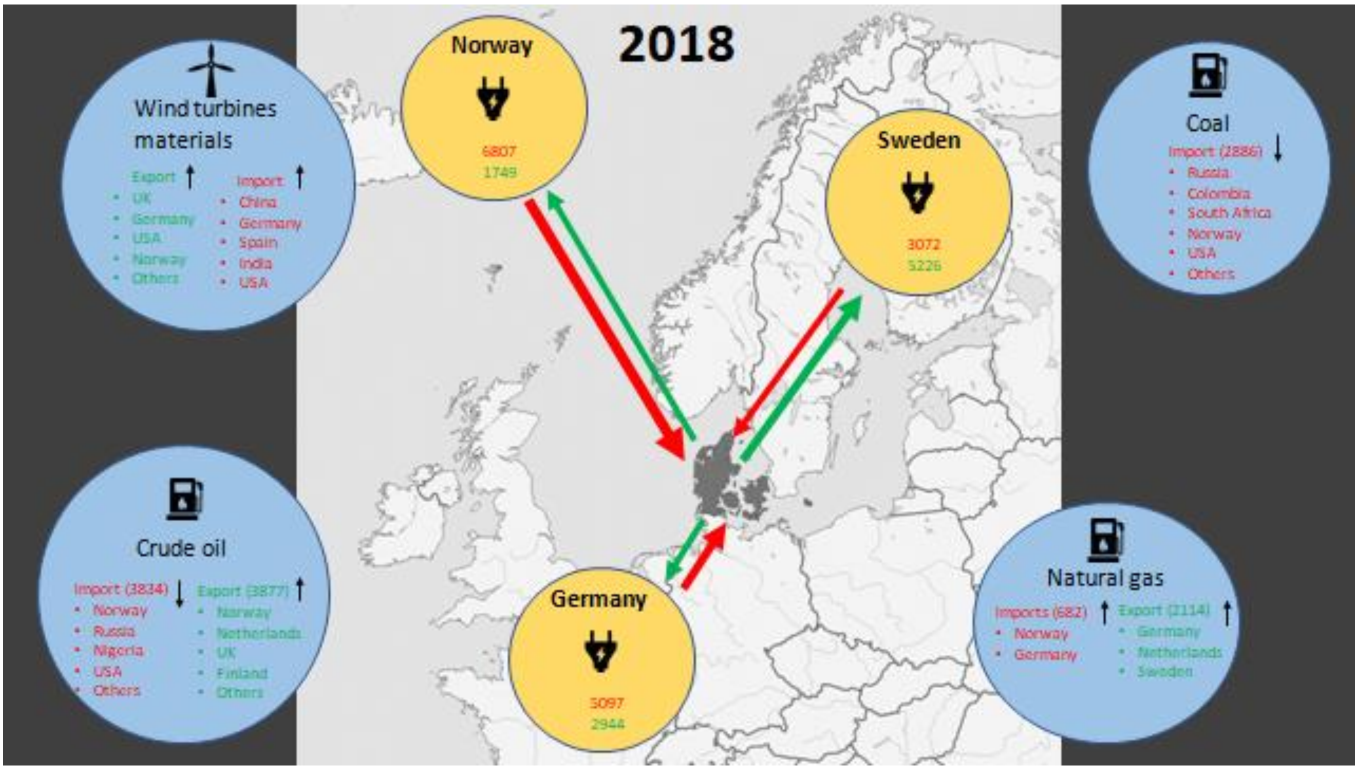

Figure 12. Import and export flows of Denmark in 2018. Electricity streams are in GWh, coal and oil in 1000 tonnes and natural gas in million m^3. Based on information from Danish Energy Agency (2018)

3.4.3 Interstate energy relations

The third step of the framework involves assessment of the interstate energy relations in 2018. The following three steps are undertaken. An energy security analysis, outline of policy means and considerations and the induced patterns of cooperation and conflict.

Energy security

Security of supply

The most important way to **provide flexibility**, has been to connect Denmark to other countries. As the previous section shows, Denmark has increased interconnection capacity over the last decades so that fluctuations in electricity generation could be spread over a larger region. Several interviewees mention interconnection as the most important manner to maintain grid balance. Some of the interviewees even stated that high penetration of wind energy would not have been possible without these interconnections.

Other flexibility options have been scarcely used over the years. Regular curtailment has not been necessary in Denmark thus far (Nycander, Söder, Olauson, & Eriksson, 2020). According to two interviewees (personal communication, 25 June and 3 July), curtailment has only been used once or twice over the last decades. Key questions like who is going to pay for the curtailed energy still needs to be answered before this option can be employed on a larger scale. Electricity storage has also barely been used over the last decades. It is simply not efficient and economically viable. Sector coupling is another flexibility option that that is not yet applied on a large scale but is assumed to play a more important role in the future.

Denmark did not have **strategic reserves** in 2018. The absence of these strategic reserves means in the case of Denmark that security of supply is high enough and that there are sufficient alternatives to deliver electricity in exceptional situations (i.e. through interconnectors). For example, if there are problems at the Danish-German border, Denmark can still import from the Nordics. According to Morten Pindstrup (personal communication, 30 July) there is a possibility that Denmark cannot deliver electricity to its customers if for example all interconnectors would be blocked. However, the fact that Denmark does not have strategic reserves means that there is trust in the system and in these interconnectors. While strategic reserves are currently not used, they might be needed in the future. Energinet (2018b) shows that the risk that electricity will not be available from 2025 onwards increases. Energinet is therefore looking into the options of temporary strategic reserves in the future.

Dependency

Denmark still **imported** 100% of its coal in 2018, and thus **dependent** on other countries. However, the share of electricity generated by coal reduced significantly.[29] The influence of this dependency on energy security has therefore diminished. Since 1993, Denmark has been a net-exporter of crude oil. Likewise, Denmark has been, and still is, a net-exporter of natural gas. Regarding electricity, 44% of the total electricity consumption was imported and 29% was exported in 2018 (International Energy Agency, 2019). More than half of the interviewees state that Denmark depended on its neighbours in maintaining grid balance and to deliver electricity in times of low wind speeds. None of the interviewees, however, consider this dependency as problematic. Peter Markussen (personal communication, 23 July) highlights for example the socio-economic benefits that arise from these electricity trade relations. He states that Denmark does not consider the dependency as a challenge but mainly as an opportunity, a way to generate revenues.

Exact numbers on the **import dependency** of materials used for the construction of wind turbines were not found. Two interviewees mention however that Denmark depends on imports of steel, which is needed for wind turbines (Bo Riisgaard Pedersen & Mary Thorogood, Personal Communication, 10 and 13 July). To obtain this steel, Denmark largely depends on the EU. While steel imports do not form a problem yet, both interviewees mention that it is important to consider the issue to avoid import problems in the future. Furthermore, Denmark depends on the import of rare earth elements which are needed for the construction of certain types of wind turbines. While Denmark does not extract these elements itself, and is thus 100 percent import dependent, most interviewees do not consider this dependency as a big problem. Different experts acknowledge that dependency might be a challenge. They however all believe that if it becomes a serious problem, a new design in which less rare earths are needed, will arise. Aidan Cronin (personal communication, 23 July), for example, states that the market is currently looking into ways to recycle rare earths and looking for alternatives that can be used. Hence, import dependency of rare earth elements is not yet considered to be a major problem for Denmark.

Coal was mainly imported from Russia. The **relation** between Denmark and Russia can be **characterised** as relatively cool, both countries have never been at war and relations were normal for a long time. However, after the annexation of Crimea, Denmark publicly voiced its condemnation and tensions evolved between the two countries (European Values Center for Security Policy, n.d.). Especially on the issue of human rights violation, opinions of both countries clash. The arising frictions between the countries are thus far not assumed to be a problem for the Danish electricity security since they are not severe and if they will become more serious one day, coal can be imported from other countries as well.

Diversification

The Danish **electricity generation mix** was quite **diverse** in 2018 and consisted of more than 7 different energy sources. 47% of the electricity was produced by wind energy, 21% by coal, 17% by biofuels, 6% by natural gas, 5% by waste, 3% by solar energy and 1% by oil (International Energy Agency, 2019).

Besides the electricity generation mix, **suppliers** of fossil fuels and electricity were **diverse** as well. 64% of the imported coal came from Russia, 14% from Colombia, 6% from South Africa and the

[29] Share of coal reduced from 91% in 1990 to 21% in 2018 (International Energy Agency, 2019).

other 16% from four other countries (Danish Energy Agency, 2018). Consumers and suppliers of oil and natural gas were also diverse. Since only a very small part of electricity was generated by these two fuels, the suppliers and consumers are not assumed to largely influence energy security. They are hence not further discussed here. Electricity was still imported from and exported to Sweden, Norway and Germany.

Diversification of generation and distribution companies has greatly increased since the liberalisation of the electricity market in 2003. From then on, consumers and households were also able to produce electricity. The market share of the largest generation company is 32,8% (EUROSTAT, 2019b). The increased number of generation and distribution companies has also increased competition on the Danish electricity market. The generation and distribution company portfolio are hence varied enough that it is not assumed to be a threat for energy security.

Price stability

Electricity prices have been **fluctuating** due to the variable production of electricity produced by wind energy. In times of high wind speeds, electricity prices were low or even negative and in times of low wind speeds, prices were high. There exist several different support schemes for electricity generators in Denmark. Two examples are price supplements and price settlements in which producers receive a fixed support in addition to the market price or a varying support in relation to the market price (Danish Energy Agency, 2017b). These sorts of schemes should reduce the risks for investors. Ekaterina Moiseeva (Personal communication, 9 July) also described how prices in Denmark to a certain extent depend on electricity prices in neighbouring countries because of market coupling. The extent to which prices are affected depends on the available transmission capacity. The more transmission capacity is available, the more prices are affected. In general, market coupling helps to stabilize domestic market prices.

Denmark had the highest **electricity price levels** of Europe in 2018. Electricity in Denmark was 31,25 eurocents per kilowatt-hour while the average European price was 21,10 eurocents. These prices are including taxes and levies. If we look at electricity prices excluding taxes and levies, Danish prices were 10,11 eurocents, which was below the European average electricity price of 12,80 cents. In sum, electricity generation costs are lower in Denmark than in most European countries. The final price for consumers is, however, higher due to high taxes and levies that the Danes pay for electricity.

Innovation and research

Denmark still has a high RTA. Zachmann and Kalcik (2018) found an **RTA** of 0,95 in Denmark between 2012 and 2014. Likewise, Bonnet et al. (2019) found a high rating of 0,85 between 2004 and 2014. The high rating reveals a high absolute number of patents and Danish advantage in the wind energy sector. Another reason that the number is this high, is that Denmark is a small country in which the limited amount of resources forces them to focus on a restricted number of technical sectors (Bonnet et al., 2019). Furthermore, Wind Europe (2017) found that Denmark hold 21% of all wind energy sector patents in Europe in 2014. The only country which has more patents is Germany, who hold 45% of the patents. Zachmann & Kalcik (2018) noticed that Denmark, Germany and Spain together accounted for 43% of the global wind turbine patents between 2012 and 2014. They point out that Denmark and Spain have more patents than their size would suggest.

The Danish specialization in the wind energy sector and large amount of present knowledge is confirmed by interviewees. Various stakeholders emphasized the significant Danish know-how knowledge on the wind industry. This knowledge involves more than just knowledge on specific technologies, it entails knowledge on the entire system and how large amounts of wind power can be penetrated into the system.

Safety and reliability

Electricity supply was **interrupted** for 20 **minutes** per person in 2018. Between 1990 and 2018, the average electricity outage was 40 minutes per person, which means that output has been stable in 99,9% of the time (Danish Utility Regulator, 2019). Electricity outages was hence not a problem for energy security.

While the Danish system has not been attacked, the threat for cyber-attacks has increased according to Thomas Egebo (personal communication, 4 August). **Cyber security** is becoming a bigger threat in almost all sectors. The electricity sector would, however, very seriously be affected and that would have enormous consequences.

Resilience and adaptive capacity

As the share of thermal power plants decreased and the share of wind turbines increased in the Danish electricity system, additional **grid operation services** were needed in 2018. To safeguard grid balance and guarantee a certain technical quality level, Energinet buys ancillary services (Energinet, n.d.). These services can be activated manually or automatically, and are important for safeguarding energy security.

Competition and markets

Income from export of wind turbines or wind turbines components added 2,25% to the Danish GDP in 2017 (Vindmølleindustrien, 2018). Furthermore, revenues from electricity production contributed to 0,5% of the total GDP in 2018 (Statista, 2020).[30] These numbers shows that the wind energy sector is contributing to the Danish economy. Especially the export flows of wind turbines and their components must be secured.

The Danish TSO, Energinet, shares **decision rights on cross-border electricity** with TSOs that Denmark is trading electricity with. Hence, two parties are sharing decision rights on each interconnector.

Policy considerations

Based on the Danish energy security situation in 2018, there are three main policy goals distinguished. The goals, employed strategies and used tools to achieve the goals are discussed here.

Increase affordability

The first identified policy goal is to increase affordability of green electricity. As explained in the previous section, various support schemes have been, and are still, necessary for most of the wind energy generators. High electricity taxes also significantly increase the electricity price for consumers. The Danish government therefore aims for a market-driven green energy transition, that is cost-effective and in which the costs for society, individuals and end-users are considered (The Danish Parliament, 2018). The strategy used to increase affordability of the transition is twofold. First, subsidies for renewables should be harmonised and simplified. A concrete way to do this is by introducing technology-neutral tenders. Subsidies become subject to competition in these open tenders, which are not only open for wind energy technologies but also for other renewable technologies. This should help to deliver the cheapest possible renewable energy. Second, taxes on energy must be reduced. Since Denmark has the highest electricity taxes in the EU, reduction of these taxes will increase the affordability of electricity, especially for low income groups. One of the potential tools to do so is the introduction of a dynamic electricity tax, in which price levels vary throughout the day, depending on the level of demand and the amount of electricity produced by wind. Reducing electricity taxes is assumed to contribute to the electrification of the energy system.

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[30] GDP is assumed to be 352058 million $.

Enhance regional cooperation

Interstate cooperation has proven to be a fundamental part of the energy system in 2018. The policy goal, as illustrated in the national energy plan of 2018, is hence to increase regional cooperation even further. The plan states that the transition leads to an increasing dependency on a well-functioning integrated electricity market (Energi- Forsynigs- og Klimaministeriet, 2018). Likewise, Energinet (2018b) stresses the value of close cooperation with European countries and the Nordic region for the Danish electricity system as well. The employed strategy to increase this cooperation is not only to invest in additional interconnector capacity, but also to increase cooperation on technological development and on value chains (Energinet, 2018a). A concrete example of a tool used to achieve this is the 'Joint Declaration', which has been agreed upon by the governments and TSOs of Denmark and Germany in June 2017 (Danish Utility Regulator, 2019). The declaration states that the transmission capacity between Denmark and Germany must gradually increase until 1100 MW in 2020. While such a tool creates trading opportunities between the two countries, it has disadvantages as well. It affects biding incentives of market parties and it increases the risk of market manipulation (Nord Pool, 2019). Hence, these kinds of policy tools can be valuable, but they also involve new challenges for which additional policy instruments might be necessary.

Boost export of green energy solutions

The third policy goal is to further increase export of the extensive Danish know-how knowledge on the wind power sector (The Danish Parliament, 2018). Denmark's high RTA and its frontrunner position in the offshore-wind industry creates opportunities to reap the benefits from this position. This can be done through the creation of bilateral collaborations with public authorities is foreign countries. Tools that can be used for that are as follows: intensification of promotion activities, extension of current export schemes, posting of new energy advisors and increase of cooperation with authorities in future growth markets via private-public partnerships.

Interstate relations of cooperation and conflict

The following section describes forms of cooperation and conflict in terms of nature, intensity and duration.

Cooperation

Four major forms of interstate cooperation are distinguished in the Danish wind energy system: cooperation on electricity generation, cooperation on wind turbine construction, cooperation on electricity distribution and cooperation in terms of knowledge sharing. We will first discuss the cooperation on electricity generation. Poul Erik Morthorst (personal communication, 3 July) emphasizes the importance of different sources in different countries for electricity generation. It is for example, extremely valuable that Norway has hydropower and that Denmark has wind energy. The stable and unstable character of these sources complement each other. Cooperation between countries becomes more effective if countries recognize that they have different sources to produce electricity from.

Furthermore, we have seen that supply chains of wind turbines have evolved over time. Mary Thorogood (personal communication, 13 July) describes how various European countries such as Germany, Denmark, the Netherlands and Spain are involved in the supply chain of wind turbines and all play an important role. Different markets have different strengths. It is important to recognize and make use of these different strengths, so that a win-win situation arises for all involved countries. Bo Riisgaard Pedersen (personal communication, 10 July) also emphasizes the importance of this cooperation. He states that European countries understand that working together in the wind industry, helps them to achieve their common goal: generating cheap, green electricity. As long as all countries get a share of the pie, they are willing to cooperate and import from one another. Additionally, Aidan Cronin (personal communication, 23 July) describes how collaboration between companies in the wind industry has optimized volumes of components, led to lower prices and higher quality. The propensity of nations to cooperate should not be considered evident in this industry. Thorogood and Pedersen both describe how countries in Asia or states in America, struggle to work together. These countries and states try to organize their own manufacturers rather than working together. This slows down the rollout of wind turbines.

Third, international cooperation is identified on electricity distribution. Denmark is part of the Nord Pool electricity market through which electricity can easily be traded between countries. Various interviewees highlight the importance of this well-functioning market for successful cooperation. Sufficient interconnector capacity between the different countries are essential for this trade too. Denmark is therefore trying to increase interconnector capacity, among others by expansion of interstate grid connections to the Netherlands, the United Kingdom and Poland. The nature of these forms of collaboration is mainly via the power exchange market. On this exchange market, electricity is traded every day since Denmark joined Nord Pool in 2000 so the intensity is high.

The last form is cooperation in terms of knowledge building and sharing. Professors from Danish universities mention the large amount of partnerships that Danish universities have with foreign universities to share knowledge. Ignacio Marti Perez (personal communication, 6 July) portrays the collaboration between the Technical University of Denmark and universities all over the world. Furthermore, Denmark is sharing knowledge on other levels as well. Kenneth Hansen (personal communication, 25 June), for example, describes how the Danish Energy Agency is collaborating with 16 different countries all over the world to boost wind energy deployment those countries and teach these countries on how to penetrate large scale of variable renewable energy. These programs fall under the DEA Energy Partnership Program (DEPP), which is part of the Danish commitment to fulfil agreements of the Copenhagen Climate Summit in 2009. These agreements encompass Denmark sharing knowledge and assisting emerging economies to decrease their carbon dioxide emissions. Another example is that Denmark tries to set up new wind energy market abroad through collaboration with embassies. The nature of these forms of cooperation is mainly bilateral and temporary.

Conflict

No significant electricity related conflicts between Denmark and other countries have taken place in or around 2018. There were, however, some small tensions on the borders between Denmark and its neighbours. First, on the Danish-German border there was some pressure from Denmark on the available German transmission capacity. The German TSO TenneT was suspected to systematically limit the available interconnection capacity between West Denmark and Germany (European Commission, 2018). The concerns were that Germany was discriminating against non-German electricity producers such as Denmark and Norway who could produce cheap electricity from wind and hydropower. The Commission therefore started an investigation to assess whether TenneT breached the European antitrust rules. In response of this investigation, TenneT offered commitments to address the worries. This commitment was that TenneT guarantees a certain percentage of the interconnector available for foreign electricity.

Another example of a tension on cross-border trade goes back several years. Peter Markussen (personal communication, 23 July) mentions a disagreement between Denmark and Sweden in 2010. By that time, Denmark complained on discrimination on access to Swedish bidding areas. Therefore, Denmark wanted that Sweden would split up into four different bidding areas rather than just one. To calm down the tensions, the EU interrupted. The disagreement ended as a minor tension, but it was not very helpful for the relation between Sweden and Denmark. While both examples should unquestionably not be considered as conflicts, they are assumed to be worth mentioning because of two reasons. First, they illustrate that cross-border trade can induce tensions between countries. Second, in both cases interruption of the EU was needed to calm down the tensions, which shows emphasises the importance of an overarching, regulation making body in an integrated electricity network.

In conclusion, this chapter has applied the previously constructed frameworks to the case of wind power in Denmark. The chapter has outlined the technical, geographical and economic characteristics of the Danish electricity system in 1990 and 2018. An energy security analysis was consequently conducted to identify any insecurities in both electricity systems. Policy consideration and means used to remedy these insecurities were outlined and the patterns of cooperation and conflict resulting from the shifted energy policies were presented thereafter. This chapter has hence described various system characteristics of the electricity sector in 1990 and 2018 in a similar fashion. Two 'portraits' of the situation in 1990 and 2018 are created, which are compared in the following chapter.

4. Case comparison

The following chapter involves the last step of the framework of analysis: the case comparison. This chapter consists of two parts. The first part outlines the most important differences and similarities in the interstate energy state relations of Denmark between 1990 and 2018. The results of the previous chapters are compared, and the major changes and resemblances are identified. The second part involves an analysis of the differences in a geopolitical context. The main aim is to assess the extent to which the changes in interstate energy relations can be attributed to the technical and geographical characteristics of wind energy or whether there were other contextual factors that played a role.

4.1 Major differences and similarities

The interstate energy relations between 1990 and 2018 are analysed and compared. Seven key differences are identified.

- **Reduced dependency on imported fossil fuels.** Coal imports reduced by 70 percent in 2018 as compared to 1990. Furthermore, Denmark became a net-exporter of oil between 1990 and 2018. Denmark thus reduced its dependency on fossil fuels from foreign countries and became more self-sufficient in that regard.

- **Intensification of market-based electricity trade, inducing interstate dependencies.** Interconnector capacity between Denmark and its neighbours has been increasing, leading to bigger import and export flows of electricity. Most of this electricity is traded via the Nord Pool exchange market, which is different compared to 1990, when electricity was mainly traded via bilateral contracts. While Denmark was exporting a great part of its produced electricity in 2018, the country was importing an even larger part that year. Especially in times of low wind speed, Denmark thus depends on its neighbours to secure electricity supplies. Yet, the sort of dependency differs from the dependency on fossil fuels. Coal is for example imported by one country and exported by another country. The supplying country depends on the consuming country for revenues but not for the good itself or their energy security. Trade relations concerning electricity are more dynamic. Denmark depends on Norway in times of low wind speed, and Norway also depends on Denmark is dry years. This can for example be seen by the high import and export peaks in Figure 11. As this figure illustrates, import and export rates vary greatly per year. Denmark depends on its neighbours and its neighbours also depend on Denmark, inducing a more symmetric dependency. Furthermore, the countries have a long history of good relations and great trust, which (partly) explains why none of the interviewees considers the Danish dependency on its neighbours as problematic (Appendix C). A better integrated electricity network is assumed to add stability and security to the market.

- **Regionalisation of energy relations.** Whereas Denmark used to import fossil fuels from countries all over the world (e.g. Colombia, USA, and Australia), the major trading partners of Denmark were countries in the Northern European region in 2018. Imports of fossil fuels from countries throughout the world decreased, and regional trade of electricity increased. Furthermore, Danish trade partners on wind turbine components are mostly countries within the Northern European region.

- **Increased political influence through the sharing of knowledge.** Denmark is gaining political influence by starting new forms of cooperation in which the country shares its know-how knowledge on the wind power sector (Appendix E). Denmark uses its extensive experience in the industry as export product and to open doors to foreign countries. It uses existing connections, but builds new ones as well. Via embassies, universities and governmental institutions, Denmark is constructing new forms of cooperation. While Denmark is a small country with a minor political impact, it has serious influence in the global wind energy sector. As Mary Thorogood (personal communication, 13 July) describes it: "Denmark punches above its weight in terms of energy policy".

- **Increased interstate cooperation on supply chains of wind turbines.** As compared to 1990, Denmark was increasingly working together with other European countries on the supply chain of wind turbines in 2018 (Appendix E). Companies in the field realize that cooperation helps to optimize the supply chain, reduce costs and that it leads to higher product quality. Aidan Cronin (personal communication, 23 July), describes for example how Denmark depends on the Dutch installation fleet. The Netherlands is frontrunner in installing offshore wind parks. For the construction of new parks, Dutch installation companies are therefore needed. The Dutch, on the other hand, also need the Danish and the Germans for the supply of wind turbine components. Increased cooperation and new forms of dependencies can hence be observed in the wind power supply chain, in which Northern European countries make use of each other's strengths and different specializations. Strong cooperation on the supply chain is not as trivial as it might seem, and is not the same in every part of the world. Developing countries or certain States in the US aim to localise wind turbine supply chains to create job opportunities and economic growth rather than to work together with other countries (Appendix C).

- **Increased dependency on critical materials.** One of the major issues in the literature on renewables and geopolitics is the dependency on critical materials. Various academics describe how these materials might be used as strategic goods and increase political influence of exporting countries. Denmark shows that it indeed depends on critical materials, but that this. dependency is considered to be a concern or a challenge rather than a serious problem. Still, the dependency on critical materials should not be ignored. It is important for Denmark and Danish companies to be aware of them being dependent on critical materials so that they can come up with strategies to reduce the dependency.

- **Increased threat for cross-border disagreement.** As cross-border trade has gained importance over the last three decades, availability of transmission capacity has become more important as well. Denmark depends on these cross-border interconnectors to maintain stability on the grid. On the other hand, since the number of interconnectors has increased, each individual interconnector became less important. Still, the threat of cross-border disagreements has increased. While these disagreements or tensions are extremely unlikely to lead to serious conflicts or wars, it is important for Denmark to keep investing in good relations with its neighbours and to pursue open and transparent communication about potential future changes.

Besides the major differences, similarities between interstate energy relations in 1990 and 2018 are identified. Denmark has learned from the oil crisis in 1973 and understood that depending on only one country for supply or demand, can be risky. The country has therefore had a diversified mix of trade partners from 1990 onwards. Denmark has not been in any energy related conflict over the last three decades and trade relations have been peaceful since 1990. Lastly, Denmark has been an exporter of natural gas and oil in 1990 and 2018.

4.2 Reflection on findings

The previous section has outlined the seven major changes in the Danish interstate energy relations. The goal of this section is to assess to what extent these changes can be attributed to the characteristics of wind energy. Since the different changes might have deviating causes, it is important not to lump them together. This section will therefore reflect on the changes one by one. Table 6 summarizes the findings. The green highlighted causes have to do with the geographical or technical characteristics of wind energy and the causes highlighted in orange concern contextual changes.

1. Reduced dependency on imported fossil fuels

The reduced dependency on imported fossil fuels can to a limited extent be attributed to the characteristics of wind energy. Around 1990, the Danish government wanted to diversify its electricity mix and increased the use of domestic sources. The diminished import dependency of fossil fuels can hence partly be attributed to the government's employed strategy, aiming to diversify their electricity generation mix and encourage the use of domestic energy sources. While the decreased dependency might seem an obvious consequence of this policy aim, it is not. As described in section 3.1, the Danish government first tried to diversify its electricity mix by the integration of nuclear energy. Due to strong public opposition nuclear energy was abandoned from the Danish energy mix. Public acceptance is thus essential for the integration of new energy sources. Widespread public support of wind power has hence influenced the smooth integration of wind energy and the reduction on imported fossil fuels. The shift can also partly be explained by the optimal Danish wind conditions. Denmark could reduce the dependency on fossil fuels thanks to these good wind conditions.

2. Intensification of market-based electricity trade, leading to higher interstate dependencies

The increase in electricity trade can, to a certain extent be attributed to the characteristics of wind energy. The variable nature of wind energy forces TSOs to provide flexibility options. In Denmark, this flexibility is delivered through interconnector capacity that enables cross-border electricity trade. The variable nature of wind has hence induced greater cross-border electricity flows.

The variable character of wind is, however, not the only reason for increasing interstate dependencies. Interconnector capacity between Denmark and its neighbours was already available before wind power was penetrated into the system, implicating that there are other reasons and benefits as well. First, and most important is the possibility to generate revenues. Denmark was aware of the fact that, in times of high wind speeds, they could sell wind power to foreign countries where electricity prices were higher. On the other hand, when wind speeds were low, they could import cheap electricity from Norway or Sweden. In this way, the trading of electricity offers countries the possibility to generate revenues. The establishment of the Nord Pool exchange market in 2005 is considered as an important facilitator of these revenues. Through this power exchange market, it became a lot easier to trade electricity in an open and fair manner.

Another factor that played a role was the EU energy policy. The EU published its Third Energy Package in 2009, in which several policy measures were focused on the construction of a single EU energy market for electricity. One of the measures was the foundation of the Agency for the Cooperation of Energy Regulators (ACER). This new body was established to help the national energy regulators to collaborate and to ensure an efficient functioning of the internal energy market. Furthermore, development of European standards and the drafting of network codes was done through the European Network for Transmissions System Operators for Electricity (ENTSO-E).[31] These new bodies and the facilitating policy of the EU are assumed to encourage cross-border trade of electricity. However, since Denmark was already strongly connected to its neighbours before this policy was put into place, it is not considered important for the increasing electricity trade relations between Denmark and the other countries.

Furthermore, the geographical location of Denmark has most likely played a role as well. Good wind conditions (i.e. high wind speeds and the great possibility for offshore production) have contributed

[31] Previous to ENTSO-E, standards were set via Nordel, which was a body for cooperation between the TSO's Denmark, Finland, Iceland, Norway and Sweden.

to the fact that the Danish government started to invest in wind power. They understood that these good conditions enabled them to generate revenues. Furthermore, the fact that Denmark has a lot of neighbours, or countries in its close neighbourhood made it easy for them to trade electricity. The role of these neighbours was particularly important since they have stable hydropower, which is a good addition to variable wind power. If Denmark, for example, would have been a remote island, electricity trade relations would probably have been less.

The last factor that might have played a role in these intensified trade relations is the great trust, especially among the Nordic countries, and the similar cultures of these countries. In March 1962, the governments of Sweden, Denmark, Norway and Finland signed the Helsinki Treaty. The main aim of this treaty was to strengthen and promote the close ties between these countries and to extent the scale of cooperation between them. Furthermore, the treaty intents to unify laws within the countries as much as possible. The long history of good relations between the Nordics is illustrated by this treaty. They trust each other and have similar cultures. The fact that these countries do not consider dependency on each other as problematic might for example be a result of this treaty.

3. Regionalisation of relations

Regionalisation of electricity trade partners can, to a certain extent, be attributed to the technical characteristic of wind power. Transportation options of electricity generated through wind power, are limited because of the electric nature of this electricity. It can therefore only be transported through electricity wires for which a physically integrated network is required. Furthermore, transportation is characterised by high losses, which makes long distance transport inefficient. This is probably the most important element that explains a regionalisation of trade relations. The design of wind turbines contributed to the regionalization of energy relations as well. It is not efficient to transport most of the heavy components, that wind turbines are built of, over long distances. The good relations Denmark is holding with its neighbours might be another part of the explanation. There is a lot of trust, especially between the Nordics, but also between the other Northern European countries, making them high valued trade partners.

4. Increased political influence through knowledge sharing

The increased influence obtained by knowledge sharing can in a certain way not be attributed to the technical and geographic characteristics of wind power. Each country that would invest heavily in the technology has the potential to become frontrunner and could use the obtained knowledge as export product. The specific characteristics of wind have limited influence on that. On the other hand, one could argue that Denmark’s geographical position did have some influence on the fact that they could acquire all the knowledge and experience in the wind energy sector. The optimal wind conditions in Denmark allowed them to test and optimize their designs. Furthermore, Demark being surrounded by three countries to which they could export wind in times of high wind speeds, and from which they could import in times of low wind speeds (especially because of stable hydropower and Norway and Sweden) helped them to gain experience on integrating wind power. This could have been much more difficult for countries without neighbours, and in particular for countries without neighbours who have hydropower as a stable source. It is, however, difficult to estimate how much expertise Denmark could have obtained if it was positioned somewhere else. Hence, it is argued that political influence because of knowledge sharing can mostly be attributed to other factors than the geographic location of Denmark. Four factors are distinguished. First, in 1985, the Danish government officially rejected nuclear power from their energy mix. Wind power was seen as one of the key alternatives for nuclear energy, and so the plan to ban nuclear was an important driver for the introduction of wind (IRENA-GWEC, 2013). Second, the decision of the Danish government to invest in the technology and create a long-term vision and stable energy policy was very important. This gave businesses and research institutes trust and assurance to invest in the wind turbine sector. Third, the increased influence by knowledge sharing can be attributed to the fact that Danish companies were first mover in the sector and recognized the wind power industry as a way to generate revenues. They were able to develop business models, through which they could earn money, giving them a frontrunner position and allowing them to share knowledge. The last important factor that should be mentioned is climate concerns, raised by the Danish government, due to various international reports and agreement (such as the Brundtland report, Kyoto Protocol and the Paris Agreement). Denmark realized that they have a minor influence in terms of global emissions compared to other countries. To significantly reduce emissions on a global scale, the focus should be on bigger, more heavily emitting countries. Denmark therefore wants to share knowledge and experiences with other countries to works towards a greener world together. The willingness to become greener is captured in the Copenhagen Climate Summit 2009. This agreement points out that Denmark should actively support emerging economies in their energy transition.

5. Increased interstate cooperation on supply chains of wind turbines

The increasing interstate cooperation on the supply chain of wind turbines cannot be attributed to the characteristics of wind. The fact that countries work together on this supply chain can merely be explained by the fact that countries see it as an opportunity to benefit from each other’s strengths and to optimize the supply chain. Cooperation is largely driven by economic thinking and free market functioning.

6. Increased dependency on critical materials

The dependency on critical materials should be attributed to the technical characteristics of wind energy production, i.e. the design of wind turbines.

7. Increasing threat for cross-border disagreement

The variable character of wind forces Denmark to provide flexibility. Denmark has chosen to deliver this flexibility through interconnector capacity which makes the country more dependent on the availability of transmission lines. The increasing threat for cross-border tensions related to the availability of interconnector capacity can therefore be attributed to the variable nature of wind power.

In conclusion, as illustrated in Table 5 below, the changes in interstate energy relations can to a certain extent be attributed to the geographical and technical characteristics of wind. Especially the intermittent nature of wind and the geographical location of Denmark (i.e. good wind conditions and neighbours with stable hydropower) were important. There are however more factors that played an essential role in the shifting interstate energy relations. The most important of them is the possibility to generate revenues. Danish energy companies and its trade partners understand that market integration (of the electricity market and the wind turbine sector) leads to more competition, creating a stable and more efficient market that enables countries to generate revenues. Hence, the possibility to earn money has increased international cooperation and competition. Another important factor is policy. Danish and also European policy measures have contributed to the shifting interstate energy relations. Furthermore, growing climate concerns have increased the sense of urge amongst countries to act and work together. Lastly, great trust and good relations between the Nordic countries has been an important factor for the newly arising relations and dependencies between the countries. While the above-mentioned factors are all assumed to have influence, it is extremely difficult and beyond scope of this study to prove or precisely assess the extent to which these factors were important. The list should therefore merely be considered as a rough estimation, rather than an exact all-encompassing list of factors.

Table 6

Overview of explaining factors per changing interstate energy relation

Type of changed interstate energy relations	Explaining factors	Characteristic of wind (yes/no)
1. Reduced dependency on imported fossil fuels	Diversification policy employed by Danish government	No
	Public support for wind power	No
	Favourable wind conditions	Yes
2. Intensification of market-based electricity trade, leading to higher interstate dependencies	Variable nature of wind power	Yes
	Possibility to generate revenues	No
	Establishment of Nord Pool power market	No
	EU policy on market integration	No
	Geographical location of Denmark	Yes
	The Helsinki Treaty	No
3. Regionalisation of relations	Network technology and topology	Yes
	The design of wind turbines	Yes
	Great trust among neighbouring countries	No
4. Increased political influence through knowledge sharing	Abandoning nuclear power	No
	Long term, stable energy policy by Danish government	No
	Favourable geographic location to gain experience	Yes
	Being the first mover on a new technology	No
	Climate concerns – Copenhagen Climate Summit 2009	No
5. Increased interstate cooperation on supply chains of wind turbines	Possibility to generate revenues because of free market functioning	No
6. Increased dependency on critical materials	The design of wind turbines	Yes
7. Increasing threat for cross-border disagreement	Variable nature of wind power	Yes

5. Discussion

This chapter involves the results for theory, the results for practice and a reflection on the used method.

5.1 Results for theory

As described in section 1.3.3 (practical and theoretical relevance), this study adds to the scientific debate by providing evidence from a concrete case. The following of this section links the findings of this case to the existing literature on the geopolitics of renewables.

5.1.1 Reflection on literature on geopolitics of renewables

The literature section discussed five major themes through which renewables might affect geopolitics. This section examines how the findings from Denmark can add to the discussions on each of these themes. Table 7 summarizes the findings.

Interstate dependencies

The case of Denmark illustrates that the ‘make-or-buy’ decision, as described by Scholten (2018) is less straightforward than the author presents. Scholten (2018) assumes that countries face a ‘make-or-buy’ decision in which producer countries are concerned about security of demand and want to maximize their revenues, and consumer countries want security of supply and affordable energy prices. This assumption requires some nuance: while Denmark decided to produce wind domestically, it still largely depends on its neighbours in times of low wind speeds. This is mainly due to the use of interconnectors to provide flexibility. If Denmark would have used domestic flexibility options such as batteries or sector coupling, import dependencies would have been less. Yet, if countries use interconnectors to provide flexibility, not only consumer, but also producer countries are import dependent in wind energy systems. Thus, although Denmark made the ‘make decision’, it still depends on ‘buying’ electricity from other countries. The distinction between producer and consumer countries is hence less straightforward than Scholten (2018) describes. Vakulchuk et al. (2020) assume something similar: they expect that international dependencies are low if renewables are produced domestically, and high if renewables are imported. This assumption again, requires some nuance. Countries that are producing wind domestically can still largely depend on their neighbours if they use interconnectors to provide flexibility.

The dependency is however not likely to be problematic. The fact that Denmark decides to build interconnectors to provide flexibility, means that it greatly trusts its neighbours. Still, it is important to be aware of the existing dependencies.

Regionalization of energy trade relations

The case of Denmark confirms many of the assumptions on regionalization of energy trade relations. Denmark indeed shows that wind energy has led to more cooperation between countries in the region and that energy relations are regionalized, as described by Scholten et al. (2020). Interviewees also highlight how countries use each other’s strengths to overcome challenges, e.g. different energy mixes of countries (Appendix C).

Some requirements for fruitful cooperation between countries were already found in literature: mutual benefits, trust and understanding (Hong, 2010; O’Sullivan et al., 2017; Scholten & Bosman, 2016). Additional requirements identified in this study are: political stability within counties, similar cultures and priorities of countries and most importantly, the existence of a common power exchange market like Nord Pool. A well-functioning power exchange market assures countries of paying a fair price for electricity (Morten Pindstrup, personal communication, 29 July).

Critical materials

The literature shows ongoing discussions on the extent to which critical materials are going to lead to geopolitical competition or conflict. None of the interviewed experts sees the dependency on critical materials as a real problem or potential source of conflict. Interviewees from the business and the research group both confirm that it is a challenge, but that it should not be seen as a severe threat (Appendix C). Interviewees have confidence in technological progress. If critical materials become a serious problem, the design of wind turbines can be adapted. Furthermore, there is a big drive in the market to recycle or reduce the use of critical materials. Since critical materials can be found at many places, governments can also work together with companies, for example by allowing certain extraction activities or by subsidizing mining. If critical materials are going to form a true risk, companies will stop constructing the types of wind turbines that need these materials. Until that time, research institutes and industry focus on ways to reduce the use of these materials.

In sum, the Danish case confirms the statement of Overland (2019), Scholten (2018) and Scholten et al. (2020), who argue that the risk of geopolitical competition over critical materials is limited.

Know-how knowledge

Literature on know-how knowledge discusses how different technological development levels or intellectual property rights might lead to contentions between countries (Bonnet et al., 2019; Scholten et al., 2020). This is not (yet) seen in the case of Denmark. On the contrary, Denmark shows how know-how knowledge on technologies and on system integration is used to start new forms of interstate collaboration. Denmark uses know-how knowledge as export product and works together with other countries through universities and the Danish Energy Agency to foster renewable energy integration. Interviewees from energy companies and governmental organizations have described how the Danish' use this knowledge to gain geopolitical influence and how the country punches above its weight in terms of energy policy. As Kenneth Hansen (personal communication, 25 June) describes: *"In DEA we have 16 countries with which we are collaborating throughout the world. It's sponsored by the government so it is in their interest. The main goal is CO2 reduction but there is also a diplomatic part in it."* While competition over clean technology patents might still arise in the future, know-how knowledge is currently mainly used to start international cooperation. The case of Denmark confirms the statement of Criekemans (2018) that the role of technology and knowledge on these technologies gained importance in renewable energy systems compared to fossil fuel systems.

Cyber security

Thus far, Denmark did not face any significant cyber-attacks on its system. While cyber security is becoming a bigger threat for the system, parties in the energy sector are working hard to counteract the risks. The case of Denmark shows that cyber threats are growing but that it does not have to lead to attacks. Still, the future should provide more evidence on this issue.

Table 7

Comparison of literature and case of Denmark. Based on Vakulchuk et al. (2020)

Main issues	Literature	Denmark
Interstate dependencies	Low if produced domestically, high if imported	High, produced domestically and partly imported
Regionalization of relations	Regionalization and increased energy cooperation	Regionalization and increased energy cooperation
Critical materials	Important, but opinions on conflict potential vary greatly	Concern but no major problem
Know-how knowledge	Potential contention on intellectual property rights	Knowledge as export product to expand market share and gain geopolitical influence
Cybersecurity	Important	Important, considered as bigger threat than before, but no attacks yet

5.1.2 Reflection on expectations of Scholten

The work of Scholten (2018) presents a set of expectations on the geopolitical impact of renewables. Since the applied framework is based on this work, this study argues that it is valuable to use the obtained insights to reflect on these expectations. The first expectation is a shift from oligopolistic to more competitive markets. This is certainly true in the case of Denmark. Connection of different countries has enlarged the electricity market, meaning that there are more generators, and more competition. The second expectation is the increased decentral nature of production by and for a more diverged set of local actors. This study indeed shows that wind energy had led to increased decentral electricity production and an increased number of electricity producers in Denmark. The next expectation is an increasing competition for rare earth materials and clean tech know-how between countries that aim to be industrial leaders in renewable generation technologies. The case of Denmark does not yet show an increased competition between countries on rare earth elements. It is, however, difficult to say something meaningful about competition on critical materials and knowledge since it is not measured in this study. Denmark did show how know-how knowledge of renewable energy technologies and system integration became increasingly important in the international energy field. The last expectation was the electrification of the system. Thus far, electrification has been limited in Denmark but experts have highlighted the importance of electrification in the future. It is even assumed to be one of the most urgent challenges the Danish system is currently facing (Mogens Rüdiger, personal communication, 25 June).

5.1.3 Reflection on the literature of geopolitics of energy

While characteristics of the system have changed significantly, knowledge from the field of geopolitics of conventional energy can still deepen understanding on the issue. As argued in section 1.4.2., better understanding of the systemic changes was needed first, before old theories could be applied. Theories from IR, energy security and the geopolitics of fossil fuels can now be applied to the Danish case to expand understanding, and look for similarities and differences between the two fields Two general observations are done. First, IR theories help to understand and scientifically support the observations. Section 1.4.2 describes how two key theories of IR can be applied to the conventional energy systems. Realism considers energy as a strategic tool in nations' competition for great international power. Liberalism, on the other hand, argues that countries can agree on a common set of norms, on which peaceful energy cooperation can be based, whereby interdependence between countries is important (Siddi, 2017). This latter theory of liberalism offers insights to explain the observed interstate energy relations in Denmark. The case of Denmark illustrates that interstate electricity trade in which countries temporarily depend on each other, has gained importance. Interdependencies have become more equal since both countries depend on each other for electricity supplies. The common set of norms, trust and the nature of the trade partners are still very important. None of the interviewees has considered dependency on Norway and Sweden as problematic because of good relations between the countries, trust and the mutual characteristic of the dependency. These insights stem from one of the classic IR theories, i.e. liberalism.

Another finding, when comparing the field of geopolitics of conventional energy sources and fossil fuels, is that knowledge has gained political importance in renewable energy systems as compared to fossil fuel systems. The role of knowledge has been limited in literature of IR and energy security. The case of Denmark illustrates that know-how knowledge on energy technologies plays a crucial role. The Danish government is even using its knowledge to gain international political influence.

5.2 Results for practice

This section reflects on the results for practice. The first part involves practical and strategic implications for the Danish electricity system. The second part reflects on the results and puts them into a broader perspective.

5.2.1 Practical and strategic implications

Based on the findings of this research, practical and strategic implications for the Danish system are identified:

- While the increased use of interconnectors has proven to be a successful manner to provide flexibility, Denmark should consider additional flexibility options. The most important and promising option is sector coupling. Furthermore, demand side flexibility, and the production of hydrogen and ammonia are interesting options.

- The Danish government and energy companies should invest in artificial energy islands. In May 2020, Denmark has already proposed to build two energy islands of 4 gigawatts in total. These islands are essential to become truly big in offshore wind since it is far more effective to connect one big island than connecting multiple, smaller wind farms. These energy islands also create opportunities to produce hydrogen and ammonia and to work together with other countries.

- Denmark should invest in the growth capacity of the wind power sector. For example, by making harbours suitable for loading and unloading an increasing amount of heavy weight products and by expanding manufacturing capacity. Looking at the CO_2 objectives for the common decades, the wind power sector is predicted to grow very fast. Denmark should be prepared for this growth.

The strategic implications are as follows:

- If the share of wind power is going to further increase in the Danish system, Denmark should strategically decide whether it wants to export cheap electricity produced by wind power, or use it domestically. While this decision might seem trivial, it can actually have large consequences for the Danish energy sector. Using electricity domestically creates possibilities for sector coupling and for the production of hydrogen or ammonia. Exporting cheap electricity, on the other hand, allows the country to make high profits. Denmark should choose one of the strategies.

- Large offshore wind farms are mostly constructed far from the consumption location, close to borders, and therewith close to interconnectors. Transportation of electricity produced by these farms requires significant transmission capacity on the grid. This capacity is also used for interconnectors. Denmark should thus decide which electricity it wants to prioritize on the transmission lines: the newly constructed wind park or the interconnectors?

- Denmark needs to diversify its knowledge and expertise to stay relevant on a global level. Wind is a relatively mature technology and as soon as most countries have adopted it, Denmark might lose its frontrunner position. Countries or regions could start their own supply chain, making Denmark not the only country with the most knowledge on wind power systems anymore. Denmark should therefore already think about new market opportunities. Markets that help the country to stay relevant and maintain its frontrunner position, such as hydrogen or ammonia.

- Some of the transmission lines from Denmark to Norway and Sweden are relatively old and have to be replaced in the short run. Yet, it is not clear whether all these are transmission lines are going to be replaced. If Norway, for example, directly builds interconnectors to Germany and the Netherlands, they might need less capacity to Denmark. Denmark must be aware of this potentially decreasing transmission capacity and must already consider alternatives.

5.2.2 Reflection on results

This section reflects on the results and puts them into perspective. It presents a somewhat more differentiated picture of the findings. Four important matters are identified. First, while the geopolitical implications seem to be mainly positive for Denmark, it is important to bring some nuance into the debate. Denmark is surrounded by countries with enormous hydropower plants, offering Denmark the opportunity to export in times of oversupply and import in times of undersupply. It is not yet clear whether countries without neighbours with stable hydropower, will be able to do this as well. For example, if three neighbouring countries all depend on solar energy and the sun is not shining for a while, will these countries then still be able to secure their supply?

The results are, to a certain extent, based on the assumption that countries benefit from import independency. Being energy autarkic is however not per definition contributing to less conflict between countries or to more world peace. Importing and exporting energy sources creates mutual dependencies between countries, making it less likely for countries to attack each other. If all energy relations are indeed regionalized, will different energy regions than be more likely to assault each other?

Third, one of the discussed issues is the conflict potential of renewables. While Denmark did not show any significant forms of conflict or tensions, one should not underestimate the play of power. Conflict is more about the division of power than about specific technologies. It is a naive idea that the battle over power will fade away merely because the good that is inducing conflict (fossil fuels) is replaced by another good (renewable energy). New types of conflict can still arise because countries gain or lose power. Awareness of this ongoing power game is of paramount importance to avoid simplification of the narratives concerning the conflict potential of renewables.

Last, while it is assumed that an integrated European energy market is beneficial for everyone, the current criticism within European countries towards the EU can be harmful for interstate relations. One of the requirements for good cooperation is trust and openness. If these conditions are at risk, it is uncertain if everyone would still benefit from an integrated market. The ongoing COVID-19 crisis has for example shown that, in times of crisis, European interstate relations are sensitive for friction.

5.3 Reflection on methods

This section reflects on the method that was used to obtain the results. The first part entails a reflection on the reliability and validity. The latter section reflects on the constructed framework of analysis.

5.3.1 Reflection on research quality

This section assesses the quality of the research by reflecting on the reliability and validity of the findings.

Reliability

Reliability is a concept used to evaluate the quality of the research. Yin (1994) describes the main goal of reliability as ensuring minimization of errors and biases in a study. One of the most important manners to provide reliability is by well documenting the followed procedures in the study. Generating insight into these processes enables the reader or other scholars to reproduce the research (Willems & van Zwieten, 2004). This study has therefore clearly described important decision making processes concerning data collection and data analysis. Deliberations made for framework selection and construction were described first (see Appendix E). Furthermore, a coding scheme and code tree were added to give the reader insight into the main topics that were discussed during the interviews, and into the structuring process of different opinions (see Appendix C and D). The summaries of the interviews at the end of this study give the reader insight in what has been discussed.

There are however things that could have been done to further increase reliability of the study. While readers have insights in the assessment made for the framework construction, experts could have validated the constructed framework. Something else that could have been done to increase reliability of the research is verification of the findings by experts from the field. Feedback of experts might have helped to further substantiate the final results. The author has, however, deliberately chosen not to do this. While expert have a lot of knowledge on specific topics, they often do not have knowledge on each of the subtopics and will assess the results using their own perspective. Like the author of this study, experts are biased. To overcome this challenge, a great number of experts would therefore have been needed. Time constraints made this impossible.

Validity

Validation is another concept used to evaluate the quality of a research. This section reflects on the internal validity, referring to the question whether a causal relation between findings is justified, and on the external validity, i.e. to what extent the findings can be generalized (Yin, 1994).

Internal validation is a concern for researchers aiming to determine whether event *x* led to event *y* (Yin, 1994). The fourth step of the applied framework aimed to examine whether shifts in step 1 can be declared by shifts in step 3. The causal relation that is outlined in this step is an estimation rather than a proven relationship. This study does not aim, or claim, to construct a causal relation between both steps since more evidence is required. It is important for readers to be aware of this, to avoid misinterpretation of the results.

As described, external validity relates to the extent to which findings can be generalized. Generalization of the outcomes of this study can be done on basis of comparability or analogy (Boeije & Bleijenbergh, 2019). If two cases show significant similarities it is possible to transfer results from one case to another. Hence, results of this study can (partly) be applied to cases with similar characteristics to the characteristics of wind power, of Denmark and of the Danish electricity systems. Argumentation on why cases show similarities is left to scholars aiming to transfer the results. Still, some of the outcomes are to a lesser extent related to specific case characteristics but more to renewable energy systems in general. This study therefore argues that certain outcomes are generalizable. First, the possibility to generate revenues is an important reason for countries to agree on dependency on foreign countries. Second, know-how knowledge on energy technologies has gained importance in renewable energy systems. Sharing this knowledge even enables countries to increase political influence. Last, renewable energy systems, like fossil fuel systems, force governments to think about a politically acceptable balance between being import dependent and secure energy supply.

To further increase generalizability, it would be valuable if more of concrete case studies would be conducted. Having evidence from a large number of cases allows for comparison, which can in turn help to build theories or derive causal relations. Furthermore, the focus on wind energy rather than on renewables in general allows for comparison of different geopolitical implications of different renewable energy sources. More research and data from concrete cases is therefore required.

5.3.2 Reflection on framework of analysis

In order to assess how interstate energy relations shifted in Denmark between 1990 and 2018, a framework of analysis was constructed, based on the framework as developed by Scholten (2018). Since Scholten's (2018) framework was developed for a global, systematic view rather than for specific cases, this research has adapted the framework to the characteristics of wind power in Denmark. Now that the constructed framework has been applied to this case, it is time to take a step back and reflect. First, this study reflects on the variables that have been adapted or added. Second, the research reflects on the missing variables in the framework, that would have been valuable in future studies. Table 8 schematically summarizes the proposed changes to the framework that is constructed for this study. The framework as created by Scholten (2018) is reflected upon thereafter. The use of the framework is discussed, strengths and weaknesses is described and recommendations for improvement are given.

Constructed framework

Added and adapted variables

First, some variables on the geographical characteristics of Denmark have been added, i.e. coastal area and neighbouring countries. The first was included because the variable *generation potential* only focussed on onshore potential. Since offshore potential can have a significant effect on the total generation potential of a country, this variable was assumed to be a valuable addition in wind energy systems. The latter, *neighbouring countries*, was added because it gives insight in how 'easy' it is to trade electricity with other countries. The assumption was that the geographical context of countries influences the ease with which countries can trade electricity. Remote countries with no or few neighbours would have less electricity trade relations than countries with many neighbours. While the author still believes that it is important to give insight into the geographical location and context of a country, the indicators neighbouring countries is a simplification of the real situation. In the case of Denmark, for example, one would say that the country has two neighbours, Sweden and Germany. Although Norway is not a direct neighbour, Denmark and Norway are very close to each other and the countries can easily trade electricity without long-distance losses. A better indicator than the quantitative amount of neighbouring countries would hence be a description of neighbours and countries in the area.

The next added variable was *vulnerabilities in the system*. The two vulnerabilities relevant in the light of wind energy systems are energy density and the failure of components. Both vulnerabilities are tackled under other variables already. Energy density under geographic location of the source, and failure of components could have been tackled under operating systems. Hence, the variable *vulnerabilities in the system* should be removed from the framework.

Furthermore, the variable *material requirements* was changed into *critical materials needed* since it was assumed that especially these critical materials would shape interstate dependencies. Some of the interviewees mentioned, however, that non-critical materials such as steel, can also create interdependencies or problems for countries. Hence, it would have been better not to specify this variable and just use *material requirements*.

Missing indicators

A variable that should be added to the framework is the size of the country relative to connected countries. Denmark is a rather small country and its geopolitical impact is limited by the country's size. One of the interviewees mentioned for example that Denmark cannot really put pressure on Germany because Denmark is so small. Another interviewee stated that the Danish influence is as big as a statistical fault in the Northern European market. So even though Denmark can produce a lot of green electricity from wind power, their geopolitical influence is limited by their size. It would hence be valuable to add *the size of the country relative to connected countries*, as a geographical characteristic of the system.

This study has intentionally left out electricity demand since it is difficult to assess the exact location of demand. The mixing of green and grey electricity makes it almost impossible to judge where electricity produced by wind turbines is exactly going to. While it is still argued that it is difficult to assess these demand locations, it is assumed to become important in the future. If wind is going to further increase in the Danish electricity mix, more electricity might be exported or be used for the production of hydrogen or ammonia. It would be good to include at least something on where the growing amount of green electricity is going to, and whether that has geopolitical implications. This study thus proposes to add demand as new dimension.

Table 8

Proposed adaptations to the framework

Dimension	Added or adapted variables to Scholten's framework	Proposed adaptions after application of framework	Newly proposed indicators to assess wind energy systems
Source	Coastal area (km)	-	Coastal area (km)
Generation	Critical materials	Material requirements	Material requirements
Distribution	Neighbouring countries (amount)	Neighbouring countries (description of countries in area)	Neighbouring countries (description of countries in area)
	-	Country size (size of country relative to connected countries)	Country size (size of country relative to connected countries)
Demand	-	Location of demand	Location of demand
	-	Size of demand	Size of demand

Scholten's framework

This section reflects on the use of the framework and the strengths and weaknesses and gives recommendations for further improvements. The findings are summarized in Table 9.

Use of framework

Scholten's (2018) framework was constructed to systematically approach and investigate the geopolitics of renewable since such a tool or framework was missing. The main aim of the framework is to break down the multifaceted issue into controllable pieces and to structure the debate on the topic. Now that we have applied the framework we can reflect on the use of the framework in practice. We argue that the framework is indeed an effective way to generate insight into the complex issue of geopolitics of renewables. If all steps are systematically followed, one can obtain a thorough understanding of geopolitical implications. Thanks to the various steps that are distinguished, the framework is relatively simple to use. While it is possible to fill in the framework by just conducting desk research, this study argues that expert interviews are a valuable additional research method to obtain data. It might take some extra time but it is definitely worth it to deepen understanding of the situation.

Strengths

One of the major strengths of the framework is that it is very helpful to schematically present characteristics of the system and interstate energy relations of a country. It allows users to understand and describe the most important general aspects of an energy system, in a relatively easy way. The framework is a first step of structurally obtaining data in this newly arising research area. It was a pleasure for the author to work with the framework and contribute to this novel field. The interviewees expressed great interest on the topic, which made it even more pleasant to work on this study.

Another strength of the framework is that it can be applied to different situations and adapted relatively easy. This enables using the framework in various systems, countries and regions and for different types of RES. Application of the framework in these different situations allows for comparison of results, which adds understanding on the topic. Applying the framework to a large number of different cases can contribute to theory construction of this new topic.

Weakness

The identified weakness is that the links and differences between some of the steps are not always clear, and that they are sensitive for misinterpretation. It would be good give more explanation about how all concepts differ from each other, and how they should be measured. A few examples; the third step consist of energy security assessment, policy considerations and patterns of cooperation and conflict. The fact that policy considerations are solely based on the findings from the energy security assessment is, for example, not entirely clear. The policy considerations that should be discussed relate to the insecurities that were identified through the energy security assessment. This connection between both concepts requires some more explanation. Subsequently, one must outline the patterns of cooperation and conflict. It is, however, not specified what kind of cooperation mechanisms must be covered in the section. Should cooperation on electricity trade for example be included? And if yes, what is the difference between the cooperation on electricity trade that is already described in the economic characteristics and energy security assessment? A similar thing accounts for the difference between the economic characteristics in step 2 and in the energy security assessment. The economic characteristics such as trade partners and trade flows are described in step 2, and in the energy security assessment those are outlined again. While there are differences in what should be examined at each step, these differences are not perfectly clear, and users of the framework can easily mix up the steps. To further improve the framework, it would hence be good to spend some more words on demarcation of the concepts and to give a more elaborate description of the conceptualization of the framework. A more precise explanation of what is expected at each step can reduce the chance of misinterpretation of the steps.

Table 9

Summary of strengths, weakness and recommendation

	Main issue	**Recommendation for improvement**
Strengths	Easy way to generate understanding of the major features of an energy system and the corresponding interstate energy relations	
	Frameworks allows for applications in various systems, countries and regions and for different types of energy sources.	
Weakness	Some (parts of the) steps show similarities. The exact differences between these parts are not always clear, making the framework sensitive for misinterpretation.	More elaborate explanation how concepts are distinguished and what is expected at each step.

6. Conclusion

The conclusion of this study consist of three components. First, a brief overview of the most important findings is given, followed by an answer to the main research question. Limitations and recommendations for further research are discussed thereafter. The chapter ends with concrete policy recommendations for Denmark. As this study strives to extract recommendations for other countries that aim to increase the share of wind power, these are discussed thereafter. The study concludes with some brief insights in potential policy making for the EU, as the overarching institutional entity for Denmark and its neighbouring countries.

6.1 Answer to the main research question

The technical and geographical characteristics of fossil fuels have shaped interstate energy relations for decades. The ongoing energy transition increases the share of renewables in the electricity mix. Since technical and geographical characteristics of renewables differ significantly from those of fossil fuels, renewables are assumed to affect interstate energy relations in a different way. It is yet unknown how these deviating characteristics will exactly shape international energy relations. While literature on the new issue of geopolitics of renewables is slowly expanding, evidence from concrete cases is still missing. Moreover, most of the existing literature groups renewables together and does not consider the specific impact that different types of renewables might have. This study focuses on filling these literature gaps by examining the geopolitical implications of large-scale wind power in the Danish electricity system, with the following research question:

"What are the geopolitical implications of a significant increase of wind energy in the Danish electricity system?"

To formulate the final answer to this research question, the main results of this study are shortly summarized first. The results consist of two important parts. The first part outlines the observed differences in interstate energy relations of Denmark between 1990 and 2018. The second parts assesses to what extent the observed differences can be attributed to the technical and geographical characteristics of wind energy.

This research finds seven differences in Danish interstate energy relations between 1990 and 2018. First, the increased production of domestic wind power decreases import dependency on foreign fossil fuels. Second, intensification of market-based electricity trade induces new interstate dependencies. The Danish TSO has significantly increased cross-border interconnector capacity in order to deal with the fluctuating character of wind power. Denmark therefore depends on electricity imports from its neighbours in times of low wind speeds, but experts do not consider this dependency problematic. On the contrary, interviewees describe how it contributes to a better integrated, more stable market. Third, the regionalization of energy relations. Denmark used to import fossil fuels from all over the world, now its major trade partners are Northern European countries. Fourth, Denmark faces increasing political influence through knowledge sharing. The transition has induced a shift in focus from control over resources to control over knowledge. Danish parties understand this very well. Through the export of knowledge on the energy sector, Denmark is gaining worldwide political influence, and the market share of Danish wind power companies is increasing. Fifth, this study recognizes an increased interstate cooperation on the supply chain of wind turbines. Wind turbine companies realize that cooperation helps to optimize the supply chain, reduces costs and leads to higher product quality. More cooperation and dependencies are hence observed in the wind power supply chain, in which Northern European countries make use of each other's strengths and specializations. Next, dependency on critical materials has increased. While the issue of critical materials is largely discussed in literature, Danish experts consider it as a concern, rather than as a serious problem. Countries and companies should be aware of the dependency on critical materials in order to find ways to reduce the dependency. Lastly, there is an increased threat for cross-border disagreement. Since cross-border transmission lines gained importance over the last decades, the availability of capacity has become more important as well. Still, disagreements or tensions are extremely unlikely to lead to serious conflicts or wars between Denmark and its neighbours.

The second part of the results assessed to what extent the described changes can be attributed to the characteristics of wind power. This research shows that a mix of various factors have contributed to the shifting interstate energy relations. Most of the important factors are contextual developments. Still, the shifts in interstate energy relations can to a small extent be attributed to the technical and geographical characteristics of wind power. Especially the intermittent nature of wind and the geographic location of Denmark, i.e. good wind conditions and located close to countries with stable hydropower sources, are important attributors to change. The technical system characteristics 'design of wind turbines' and 'network technology and topology' have influenced interstate energy relations as well. The most notable contextual factor that explains the shifts in energy relations is the possibility to generate revenues. Denmark and its trade partners understand that market integration (of the electricity market and the wind turbine sector) leads to more competition, creating a stable and more efficient market that enables countries to generate revenues. The possibility to earn money has thus increased international cooperation and competition. Policy, climate concerns, a well-functioning trade market (Nord Pool) and good relations with neighbouring countries are factors that also influence the energy relations and dependencies of Denmark.

Thus, what are the geopolitical implications of a significant increase of wind energy in the Danish electricity system? These come down to three major points. First, Denmark is increasingly trading electricity with neighbouring countries. Denmark even depends on these countries to deal with the fluctuating nature of wind power. Increased electricity trade has led to a better integrated Northern European electricity market, in which some contested dependencies are replaced by valuable interstate forms of cooperation. The new system allows for generation of revenues and it stabilizes the market.

Second, being first mover in the wind turbine sector has strengthened the position of Danish wind power companies. It has increased Danish export of components related to the energy sector, which in turn created job opportunities and generates income.

Last, Denmark uses the electricity sector to gain global influence. While Denmark is a small country, it is punching above its weight in terms of energy policy. The far-reaching Danish knowledge and experience opens doors to foreign countries. New partnerships do not only increase political influence, they also help to increase global market share of Danish companies.

Overall, the geopolitical implications for Denmark have predominantly been positive, driving regional cooperation, stimulating welfare growth and strengthening its position in the international arena. The Danish case could therefore be an example for other (European) countries, helping them to reduce emissions, to create jobs and last but not least, driving much needed European or international cooperation in turbulent times. In order to contribute to that process, this study ends with several policy recommendations. As further research is indispensable to continue overcoming knowledge gaps, the next section first outlines the limitations of this research and provides recommendations for further research.

6.2 Limitations and recommendations for further research

The major limitations of this study are divided into two categories, systemic limitations, i.e. limitations of the studied issue, and research limitations, which are more practical limitations of the study. Two systemic limitations are distinguished. Probably the most significant one is the fact this study solely focuses on the electricity system rather than on the whole energy system. While separation of the electricity and gas systems looks easy on paper, it is not in practice. The systems are interwoven and continuously influencing each other. Mutual interference of both systems and the fact that the electricity system is only a small part of the total energy system contribute to an incomplete image of all geopolitical implications. Second, this study focussed on the geopolitical implications for Denmark only and the shifts in interstate energy relations are outlined from a Danish perspective. The term *interstate relations* implies involvement of more than one country. Implications for countries that Denmark is trading with are at least as import to examine. For example, Denmark benefitting from less import dependency of fossil fuels implicates other countries losing revenues. Political instability might grow in these countries, leading to geopolitical destabilization in the long haul. To generate a broader picture, it would have been good if some of these implications were presented as well. The last identified limitation is a rather practical one. It concerns the lack of data on the electricity system in 1990. It was quite difficult to find good information on all the system aspects of 1990. Some data is therefore missing, making it impossible to draw a complete picture of the electricity system in that year.

The limitations above could be addressed in future research. This study was one of the first attempts to provide evidence from a concrete case in the field of geopolitics of renewables. Although the novelty of the study area leaves plenty of opportunity for further research, this study gives three recommendations.

- **Evidence from other forms of renewables**
  Future studies should focus on the geopolitical implications of other types of renewables than wind power, such as solar power or biomass. This study adds to scientific debate by focussing on the geopolitical implications induced by the specific characteristics of wind power. Evidence on the geopolitical implications of other forms of renewable energy is essential as well. Increased evidence from various energy sources helps to deepen understanding on the issue, and especially on the impact of different characteristics of different sources. Moreover, while this study has intentionally left green hydrogen and ammonia out of scope, examining their geopolitical impact would be interesting since these elements are likely to play a more important role in the future. If Denmark for example further increases wind power generation, excess power might be used to produce green hydrogen or ammonia. These elements can significantly impact interstate energy trade relations since they allow for long-distance transportation. It would hence be interesting to examine the geopolitical implications of green hydrogen and ammonia, among other (yet to be discovered) renewables.

- **Increased research on wind power**
  More evidence from case studies on the geopolitical implications of wind power is needed. The framework with newly proposed variables and indicators for wind energy specific should therefore be applied in other countries or regions. Denmark is one of the frontrunners in the transition and this study has therefore outlined geopolitical implications for Denmark. It would be interesting to do the same in other countries (especially countries located in other continents) and compare findings. Comparison can deepen the understanding of how geographical, technical and contextual factors affect geopolitics.

- **Case studies into the decreasing demand of fossil fuels**
  Future studies should examine the geopolitical implications of the decreasing demand of fossil fuels. This will probably be the number one development in the energy sector for the upcoming decades, and there still has not been much research into this question. As explained earlier, the geopolitical implications of the decreasing demand for fossil fuels might be even stronger than implications of renewables in the energy mix. Future research should therefore outline the implications of demand reductions for large fossil fuel exporting countries. That could then also shed more light on the impact of upcoming renewables in the energy mix.

6.3 Policy recommendations

This study outlines three major geopolitical implications due to the increased share of wind power in the Danish electricity mix. These implications will induce new challenges. The findings of this research and especially of the interviews, have shed light on possible ways to overcome these challenges and assure continuation of a beneficial transition. Several energy policy recommendations are formulated. First for Denmark itself, then for other countries facing a similar transition to Denmark, and finally for the EU as experts argue that the EU can (and should) play an important role in the European transition.

- **Taxes for sectoral change.** The decarbonisation of the Danish electricity system is on the right track. It is now time to focus on emission reduction in other sectors. Since the share of wind power is assumed to grow further the coming years, green electricity should be used in other sectors too. The Danish government must therefore concentrate on the electrification of sectors such as transportation and heating. Transitions of these sectors can (partly) be financed in a similar fashion to wind power financing; namely through environmental taxation. Energy taxes help to support changes in the sectors, revenues can be used for technology development.

- **Diversification of expertise.** While Denmark is big in the wind energy sector, wind power forms a limited part of the total energy sector. The Danish government should therefore think about the role they want to play in the future energy sector. To stay relevant on a global level in the long run, the country must excel in new energy markets other than wind. Doing so requires a clear, long term strategy developed by the Danish government. The strategy should entail concrete targets and stable supporting policy measures.

The outcomes of this study are also relevant for governments of other countries that aim to increase the share of wind energy in their electricity mix. The success factors of Denmark are therefore translated into policy recommendations for other countries:

- **Long term vision and stable policy are key.** Almost all experts explain the Danish success by a long term vision and strong regulatory regime employed by the Danish government. Other countries must therefore create a similar strong regulatory regime, with long-term energy strategies and policies. National governments have to formulate a clear line of sight and develop supporting and stable policy tools. This helps to build trust and certainty among investors, which is highly needed for a successful transition.

- **Share the benefits.** Among the major issues of the energy transition are consensus among parliament on energy policies and support from society. National governments must therefore focus on a system that is creating socio-economic benefits for everyone. Governments can for example emphasize job creation and highlight the economic benefits induced by the energy transition. The case of wind power in Denmark forms a valuable example since it illustrates the economic advantages that the transition, and particularly, specialization in a certain technology, can bring to a country.

- **Invest in knowledge.** In line with the first two recommendations, nations should seize economic opportunities through investment in knowledge. If governments wants to achieve their long term strategy and to create economic benefits, they should invest in knowledge. Development of expertise can help to create new domestic markets, which in turn creates new jobs and brings economic prosperity. Denmark demonstrates how being first mover in a renewable energy technology can have great economic advantages. National governments should therefore actively invest in research and development of new technologies.

Finally, policy recommendations for the EU are formulated as most of the interviewees have emphasized the important role that the EU plays, and should play in the future energy transition.

- **Intermediate in conflict.** The EU has been easing cooperation between Denmark and its neighbours by interrupting in cross-border disagreements. The EU as overarching legal entity and regulatory authority helps to overcome challenges or disagreements between countries. It facilitates better cooperation between European nations which is of significant importance for an integrated European electricity network. The EU should hence construct legal frameworks within which countries can operate.

- **Cherish the champions.** The EU pursues strong competition policy in Europe. While this policy is often beneficial, it can also hamper the formation of big companies that have power on the world market. The EU should therefore facilitate the creation of energy companies that have stronger positions on the global market, and therewith avoid dependence from other power blocks. Stronger position and powerful companies can help to set up European supply chains that are important for regional markets and to reap the financial benefits of the transition.

- **Aligning standards.** The EU should ensure a compatible market design throughout the whole continent, by making sure that initiatives and new policy measures in different countries are aligned and not contradictory. While the EU is already responsible for this market design, it is important that future support schemes or political agreements will neither distort the rapidly changing market.

This study started with an example of how limited trust between two regions, e.g. the MENA region and Europe, formed a serious hurdle to work towards a renewable electricity system that could guarantee stable electricity supply for both. The case of Denmark shows that while the transition to a renewable energy mix indeed induces geopolitical challenges, they can be addressed in an effective manner as well. It can also lead to more and deepened cooperation. Cooperation between Denmark, the Nordics and other European nations has proven successful in order to safeguard energy security, and at the same time generate revenues. Furthermore, Denmark shows that having specified knowledge on renewable energy technologies and system integration can have serious political benefits: it opens doors to new cooperation partners and it increases international political influence.

This study has contributed new insights in the factors behind the Danish success. Its recommendations can guide other nations on that path towards a more sustainable energy mix. The global transition towards renewable energy is an indispensable development, no matter what challenges we will face. The findings of this study hopefully form not only a suitable (and practically applicable) conclusion, but also a substantial contribution to that global transition.

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Appendix A Interview questions

- Personal introduction
- Introduction on topic
- Confidentiality
- Reason to approach person

Energy system and interstate relations

- The energy transition is more than just a change in the energy mix. It involves a deeper change of the whole energy system. One of the changes is the structure of the electricity market. What do you think are the most important changes of the electricity market in Denmark over the last decades that can be attributed to an increase in wind power generation? (Think about the number of market players, entry barriers, central vs. decentral character)
  Yes, many changes: Do you think that these changes can be mainly attributed to the characteristics of wind energy or are there other important factors as well?
  No, not much has changed: Are there any changes in the technical operation of the system, what do you consider as the most important ones?
  System more central or decentral?

- Some people have described Denmark as a transit country that can easily connect to the Continent but also to the Nordic countries. Would you also describe Denmark in such a way? What are the most important implications of this position for the Danish electricity sector?

- The integrated electricity network is a good opportunity for Denmark to maintain grid balance. However, in case of emergency, national governments want to be self-sufficient. How does Denmark strategize to be always able to deliver electricity to its citizens? Does Denmark for example has strategic reserves?
  Yes: When are these strategic reserves used? Are there any concrete examples in which Denmark has used them in the past?
  No: What does Denmark do in exceptional circumstances when electricity is scarce?

- Denmark produces a lot of wind energy domestically, but it still imports a lot from neighboring countries. Would you say that Denmark, to a certain extent depends on these countries to safeguard a stable electricity supply?
  Yes: is this dependency problematic?
  No: So Denmark is mainly self-sufficient and trading electricity merely to generate revenues?
  What is the role of hydropower in the Danish electricity sector? Could the share of wind energy have been as large as it is today without Norwegian hydropower?

- Next to electricity supply, are there any other areas/components in which Denmark depends on other countries in their electricity supply or in which other countries depend on Denmark? (For example, supply of critical materials, supply chain of components for wind turbine construction, knowledge, investments) → constraints to renewable energy production?
  Yes, dependent: Do you consider this dependency as problematic?
  No, not dependent: And do you think that other countries depend on Denmark?
  Does Denmark use a certain strategy to deal with import dependency of critical materials? For example, investing in extraction in other countries or building up a national stock.

- An important part of my thesis is to assess to what extent the shifts in energy relations can be attributed to the characteristics of wind energy. Do you feel that the shifts in energy trade relations and interdependencies between countries can be merely attributed to the characteristics of wind or are there more factors that were important? And if there were other elements, what would they be?
  (For example, the fact that certain countries have gained a lot of power by exporting oil can be attributed to the fact that oil is geographically bounded and can only be found in certain areas).

- Another important question in the debate is whether the increase of renewables will lead to more or less conflicts between countries. For example, fossil fuels have led to conflicts or have been used as means of conflict between countries (for example oil embargo). Are there any issues within the Danish electricity system which you consider as potential source of conflict?
  Yes: Have these issues been recurring in the Danish historical context? Conversely, are there examples of cooperation for which renewables have formed a basis?
  No: Do you assume that renewables can form a keystone for cooperation? If yes, what type of relations? (For example, long term vs short term, via market or bilateral, economic, political, diplomatic?)

- You have a lot of experience on energy cooperation initiatives. Could you elaborate further on these initiatives? What is the aim of these initiatives? What type of cooperation initiatives mainly exist? For example political, diplomatic, via market or bilateral? Why is Denmark investing in these kind of cooperations if they are already achieving their targets?

Policy/strategy

We have discussed the changes in interstate energy relations. I would now like to ask you a few questions on the Danish energy policy and its energy strategy.

- What do you consider as the most important strategy used by the Danish government to reap the benefits of the energy transition?

- What do you consider as the most important policy tools used by the government to reach the position Denmark is in today?

- Are there any important requirements for successful international cooperation on the electricity market?

- What do you consider as the most important challenges for the electricity system in Denmark from a geopolitical perspective?

- What should Denmark do in the future to overcome this challenge and reap more benefits of the frontrunner position it nowadays has? What would be a good strategy that should be employed?

Future

- What do you consider as the most important challenges that Denmark is facing nowadays?

- What are important policy tools that should be used in the future?

Wrap up

- Is there anything we haven't covered during this discussion which you think is relevant for my thesis?

- And finally, could you help me with a relevant contact in the Danish electricity sector who you feel would add value to my study?

Appendix B Summaries of interviews

Interview 1
Name: Anonymuous 1
Organization and function: -
Date: 25-06-2020

Flexibility options

Curtailment is an important discussion that is currently going on. At some days there is simple too much wind energy produced. Important questions are: Who should bear the costs of curtailment? What happens to these costs, should energy companies pay for it or governments? There is a voluntary curtailment market in Denmark. Denmark does not have a capacity market but Denmark has strategic reserves. Without other mechanism (like capacity markets and ancillary services where TSO secures production from flexible assets) power prices should go up and as periods with excess variable renewable energy production is also expected to increase price volatility in general is expected (more very high or negative hour prices). As indicated in table below we are already observing much more negative hour prices.

Interstate electricity trade

Around 10/15 years ago, Sweden cut off the flow of electricity because they wanted to keep the green electricity within their country. This led to a discussion between Norway, Sweden and Denmark about cutting of flow. Now they introduced a new rule which states that 70% of the interconnection capacity must be used. There were similar discussions on the German-Danish border. Denmark wants to export to Germany but since Germany has too little transmission capacity, there were export constraints. Now the German TSO has to pay Danish companies (most often wind generators) for ramping down production when wind production surplus is too big. By doing so wind generators are fully compensating (as we are offering down regulation at out marginal costs) and we are then held unaccountable for the excess surplus of renewable energy in the power system. As the curtailment is handled in this way – it is voluntary and a market based solution. In Denmark these voluntary curtailments are referred to as 'special regulation'. One of the bottlenecks is thus that there is not enough transmission capacity in Germany. This decreases the export from Denmark to Germany and reduces electricity prices in Denmark. One the one hand this is assumed to be negative, because Denmark has lower prices. On the other hand, it is an advantage as well because Germany pays Denmark. For Denmark, it would be good if they could increase interconnector capacity to the continent because that will increase electricity prices. I don't consider 2018 net import for Denmark as a problem as such, but it is a general problem how power markets should accommodate a continuous higher penetration of variable renewable energy. Flexible assets like coal fired power generation is phased out and CCGT are projected fewer and fewer operating hours and profit margins are low.

Requirements for successful cooperation on electricity market

Much EC regulation is about improving cross border trading by aligning products or by forcing TSO and countries to build and share interconnector capacity. One example is balance code which holds three subprojects on alignment of ancillary services. Project "Mari" and "Picasso" on Regulation Power and "Terre" on replacement reserves. Another example is EC regulation which states that TSO should offer 70% of the installed interconnector capacities for markets and that interconnector name plate capacities should account at least 15% of installed production capacity.

Energy policy

Both alignment initiatives and targets on interconnector capacities are important for a well-functioning power market and for the target on green transition. A large part of energy policy is naturally focused on targets for VRE and security of supply, but cost of electricity is likewise a policy objective. These three objectives are often interdependent and contradictory.

Interview 2
Name: Kenneth Hansen
Organization and function: Danish Energy Agency, international cooperation department India
Date: 25-06-2020

Changes electricity market

Denmark is part of Nord Pool. At the moment DEA is making a report about how power market and liberalization is taking place in Denmark. Report how the market has developed over the last 25 years. Many things have stayed the same but there are some changes. I will repeat some of the most important ones that are discussed within the report.

- Economic dispatch, least cost producing units were prioritised. Danish wind power has typically the lowest marginal costs if it is very windy. If it is not very windy, then mostly hydropower from Sweden and Norway is the cheapest and thus prioritized.
- Demand projections, intraday market of 24 hours in advance. That's where you estimate how much demand you need and where you bid in. You have to match your bids. You often have imbalances. In Denmark, there are the Balancing responsible market parties. These parties have a different market to trade.
- More wind power integration has led to a decrease in the average electricity price. There are some correlations, but it still differs a lot from hour to hour. Are lower prices problematic for electricity producers? Electricity producers want high prices. There are these different markets. The intraday market which is 24 hours before, and there are the interday markets in which you can trade within the day. There are different ways of doing that. For example, if you are a thermal power plant you can safe some of your electricity which you can use as a reserve.
- Discussions on profit vs non-profit organizations. TSO is government owned, they charge the fees and taxes but not allowed to make profits. That's also an important part of the market.

Electricity imports

Denmark has been self-sufficient for a few decades. The more wind power we are producing, the more we will export. This week, a new energy agreement is published. The most important idea is on Energy islands where you connect 2 GW of wind power, 3 GW and 1 GW. So 6 GW of wind power is build before 2030. So we will also export more wind power in the future.

To some degree Denmark depends on electricity trade with Norway and Sweden to maintain balance of the grid. That's the advantage of being close to Norway for their hydropower. This dependency is with Norway and Sweden is not problematic. You mentioned Russia before and that could be problematic. But Norway and Sweden is ok. Yes, I guess so, but also because there are common research groups between our countries focussing on energy. But your right, fuel independence is a big topic countries.

Knowledge exports

Denmark is a small country, so we can do a lot of things but on global scale it won't have a big impact. In DEA we have 16 countries with which we are collaborating throughout the world. It's sponsored by the government so it is in their interest. The main goal is CO2 reduction but there is also a diplomatic part in it.

Providing flexibility

Classic ones. Export cables, market, the forecasting (by TSO's). Smart grids are not so much used yet. In the future we want to increase coupling of the sectors. Power to heat and heat pumps are becomes more and more important. Furthermore, hydrogen will be produced at the island and will be used to produce feedstock such as ammonia.

Policy tools used by Danish government

1. Broad agreement and broad coalitions. Most of the parties are on the same page when making these agreements, and they are long-term so they won't be changed the next time we get a new parliament. That's one of the main points.
2. Promotion of wind power for many years. When we build the first offshore and onshore wind farms there was a lot of political support and subsidies were available. Moreover, we had the PSO's, the public service obligation, every time you buy electricity as a consumer, you pay a small fee that is used to build up new renewables. This has been used to build a lot of wind power.
3. Feed-in-tariffs, you got a fixed fee for the first 15000 hours full of production. Now, since 2 or 3 years it's more market based. The government has this new approach on technology neutral tenders. There is money allocated to an auction which can be all types of renewables, they are competing against each other and the cheapest wins. So before, the government used a fixed fee to stimulate wind power but now they try to support all types of renewables by these tenders.

Effect of wind energy on electricity prices

We do have negative prices where the price went below zero. We also had hours in which electricity was very expensive. So there is some margin but that's always the case. Norway has the cheapest electricity. They sell it to Denmark which has slightly higher prices. We sell it to Germany and soon to UK as well which have higher prices as well. So Denmark earns quite some money on being the bottleneck. Transmitting power through different countries.

Requirements for cooperation between countries

Trust is always good. Another thing is the shared power market which is formed by the TSO's. So there is a shared ownership. Furthermore, Norway is happy to sell their electricity to us and we are happy to sell it to Germany so there is a benefit for both parts. Besides, culture or priorities in the countries are the same, all have a big focus on renewables.

Take ways for countries that want to follow the same path as Denmark

To have long term strategies and policies in place. Industry and developers, everyone needs to start planning quick. Denmark has also a focus on job creation for public support. So not only looking at the energy but also to the social aspects. Besides, wind power has been influenced by the green ambitious of the government, 50 years ago already. And the skills in labour force and regulators. Denmark gained these skills through learning by doing.

Anything we haven't covered?

Remember how we have shifted to wind but also to biomass. There is quite some debate on it now. We are discussing the climate laws for the future. Debate on biomass is on security because we are importing 50% (from Baltics, Russia, North-America). But also on CO2 emissions, how sustainable is it? Can we get rid of biomass? This dependency on biomass cannot particularly be attributed to the fact the wind is intermittent. We could also use coal for that. The dependency on biomass is more because of the green movement and the way how the subsidy system is constructed in Denmark. We use a lot of biomass for district heating.

Interview 3

Name: Mogens Rüdiger
Organization and function: Aalborg University, Associate Professor a.o. on energy policy in Denmark
Date: 25-06-2020

Energy relations 1990-2018

Before the oil crisis, oil was coming from the Middle East. The production of oil and natural gas in North Sea began in 1972. What we see is a regularisation of the natural gas system and also the electricity system. The natural gas system became an important issue because of the Russian role in the system. But Denmark also benefited from the system because they could export to Germany. Denmark has been connected to Norway and Sweden for a long time (around first world war). Denmark had a very crucial connection with Norway. When it was rainy, Norway could export, when it was windy, Denmark could export power to Norway and Sweden. This interdependence has been very important in the way that the Danish power system has functioned until now.

Denmark is dependent on Norway and Sweden, and partly on Germany. We export to Germany. In situation of crises, Denmark could also import to Germany. Also dependent on import of coal for many years. Coal is imported from Colombia. Besides, Denmark is importing biomass and a lot of household waste from Londen for district heating. These interdependencies are not problematic, because it’s a well-functioning market. The day to day market, Nord Pool, is well-functioning. Denmark hasn’t experienced a lot of blackouts for many years. It’s partly because of the interconnections to Sweden and Norway, especially Norway. It might be a problem when it comes to the price. Normally you say that oil from Norway is quite expensive. But wind energy from Denmark to Norway is almost for free so in that sense the relation is not symmetrical. Utilities in Norway want to get a fair price for their energy. Denmark has a long tradition for overcapacity in their system, because of a non-profit system designed for utilities in the business. The outcome was that there was substantial overcapacity.

Changes attributed to characteristics of wind?

Wind is an important factor because wind energy is intermittent, so the Danish systems needs a kind of buffer. The connection to Norway and Sweden are the kind of buffer systems. I don’t think that the Danish system wouldn’t work if it wasn’t connected to these countries. The dependency is mutual with Norway ad Sweden. Germans are not that interested in working together with Denmark because they haven’t improved their grid so it is too small so Denmark cannot export what they want.

Conflict

Only controversial conflict has been to natural gas. Denmark has put a pressure on Germany to improve their grid and make it possible to export more electricity. But natural gas conflict was not substantial in my opinion because Denmark has imported very little. Pressure on Germany is small. Denmark has expressed their interest in better connection with Germany. But since they are neighboring countries they don’t want to get in conflict on this problem.

Energy policy in 1990

As a response to the oil crisis in the 1970's, Denmark made an energy policy for the first time ever. The strategy was to reduce oil and to increase diversification in energy mix. Coal was introduced as substitute for oil. Besides, the Danish government was planning to increase nuclear power but they dropped that idea and dismissed in 1985. The change of strategy resulted in very substantial use of coal in the electricity production. When the Brundtland report was published in 1987 it became clear that change was needed and Denmark sees itself as energy frontrunner and that doesn't fit with a strongly coal based energy system. The right centred government, the social liberals, asked parliament to change strategy and increase renewables. In the energy plan from 1976, research in wind energy was partly funded by the state. This lead to investors and entrepreneurs that started research into the topic. Most important policy goals during that time were: Sustainability, sustainable development, greening of the energy sector was put on the agenda. From 1990 to 1993, the government changed once more and it became a right winged government without social liberals but in 1993, a social democratic government was elected, and they were strongly committed to greening of the energy sector. They were very progressive.

Energy policy after 1990

In 2001, a social democratic government was replaced by a conservative liberal government. They wanted a new strategy on energy policy. They didn't want to build more wind miles. They wanted to stop greening of energy sector. Around 2004/2005, Denmark followed the Bush Adminstration and around that time the Bush Administration began to look into energy policy and send some signal that they wanted to change strategy. Denmark followed these new signals, and we got a new energy minister that was also interested in sustainability. A few years later in 2009, the COP was organized in Copenhagen and so Denmark had to show that they were interested in greening and climate friendly policy.

Energy policy now

Last week, the government and political parties decided that Denmark is going to build two energy islands in North Sea. Most urgent problem is to construct an energy system based on renewables. It is urgent because intermittency is a big challenge for wind energy. You have an old infrastructure based on fossil fuels. If we want to comply with the 2050 goals, we should transform the energy infrastructure. Second problem, Denmark has replaced coal with biomass and in the last few years there is a discussion going on how sustainable biomass is. I think if you would ask the energy minister, he would say that electrification is the most urgent problem.

Policy tools to reach current position

If we go back to the 70's, I would say Denmark has a very strong regulatory regime. It was constructed as response to first oil crisis. It has been transformed and adopted to the climate agenda. Denmark has a very efficient combination of market and government. I would say regulation, it's one of the strongest in Denmark. Concerning cooperation with other countries, before the oil crisis Denmark was willing to cooperate with all members of EU and Russia. But that changed in 2014 because of the Kremlin. They wanted to skip the relations. When the system becomes more and more green, there is no need for natural gas. It's also an issue to replace natural gas by PtG.

Requirements for successful integration

It is important to have some state subsidies for the establishment of new energy companies or wind parks. There were all kind of support from research to funding. Besides, I hope that EU will be able to become more visible in energy policy. They can be very helpful for East Eu countries. And, ofcourse if you want wind power than a lot of wind is important. Furthermore, strong flexible regulatory regimes, state subsidy of new utilities and a well-functioning market like Nord Pool. Because I think long term contracts are not enough, they will only go for maybe ten years or something. And technological progress but I don't think that Denmark is better than other countries. But we have a very efficient supply chain

<u>Interview 4</u>
Name: Anonymous 2
Organization and function: -
Date: 30-06-2020

Energy trends in the Nordic region

Increase of wind farms, increase of LNG terminals, LNG from Qatar, gas from Norway.

Role of governments in critical materials

Companies are the ones trading electricity. Governments create a regulatory framework and only have a subtle role in this. Energy companies need minerals for production. These minerals can be found in places far away but there is not much the government can do about that. The role of the government is hence very limited in this. In practice, it is not easy to make binding agreements on how countries must deal with these critical materials. The responsibility is mainly in hands of companies themselves.

Conflict or cooperation

The transition leads to shifting power positions between countries but renewables themselves are not the direct source of a conflict. Certain countries will gain influence and power and that can lead to political tensions. It is important to make countries aware of these implications and potential tensions. Furthermore, the transition has not only implications on the relations between states but also on the situation within countries. Critical materials are an important aspect within the transition that might gives ground for potential conflicts or tensions. On the other hand, cooperation is likely to increase because of the transition. An important example of this is the green deals. A form of international agreement in which European countries work together. However, cooperation within Europe is only a small part of the solution. Most of the emission reduction should be done in other continents.

Future and role of European Union

European Union plays an important role in future cooperation mechanisms between countries. As I said, the Green Deal in Brussel is an important example which stimulates countries to change. However, most of the emissions are outside Europe so we should be careful that we are not only focussing on European cooperation mechanisms. The biggest challenges are outside the EU. But the policy tools employed by the EU are still important. They can do a lot by regulation. For example, direct subsidies and taxes. Besides, focussing on countries that the EU can work together with.

<u>Interview 5</u>
Name: Poul Erik Morthorst
Organization and function: Technical University Denmark, Professor in system analysis and renewable energy (mainly wind)
Date: 03-07-2020

Interconnection of the system

Denmark has developed interconnectors very strongly the last decades. We started by having connections with Norway and Sweden and Germany. No doubt that these interconnections have helped us to build wind power. These connections were enhanced over the last decades and we are now also constructing connections to other countries, the Netherlands and the UK. So interconnectors are a very important part of the success of wind power. Without them we couldn't have as much wind power as we have now. So this trade between the countries is very important. And in an EU context, I'm sure that the more RES we have, the more countries become interconnected. So it is going to be further interconnected than it already is by now. The large EU market for electricity helps the integration of renewables as well. I don't see the increase of the network as problematic. We have to rely more on each other when it comes to electricity trade but until now I don't see this as a political problem. I might become a problem in the future but in general I haven't seen any problem. The mutual dependency is to a certain extent a reason why this interdependency should be less considered as a problem. It also has to do with making revenues, Norway can sell cheap electricity to Denmark.

The extent to which relations can be attributed to the characteristics of wind energy

When the interconnections started it was because of the hydropower. If we had very rainy years, Norway could export electricity, that was the way it started. But within the last 15 years, at least, wind power has gained increasing interest. Wind power is by now a very important component of the trade.

Changes in electricity system

In '80 and '90 we developed the decentralized power plants but in 2000 it was more going into the direction of wind power. Wind is pressing the large power plants out of the market. That's a reason that we rely to a lesser extent on coal fired power plants, they are pushed out of the market by especially wind power plants. The most important development, no doubt, is the development of wind power. After 2000 the system is not particularly decentralized anymore. We have large offshore wind parks so this decentralized idea is changing again. Wind power is more a central technology than a decentral technology. We have small power plants on land, but these are less important. The future development focusses more offshore wind. Furthermore, the balancing of the system has changed. The small and big power plants could take place in the development but now we see less and less plants that can do the balancing in the system. So balancing is much more done by trade and we rely on Sweden, Norway and Germany to balance the system. Germans have the same problem and we also help them.

Flexibility options

Trade is the most used flexibility option. We used curtailment only once or twice within the last decades, it is very seldom. If you curtail a wind power plant, you have to pay for the electricity so that is a problem. We do not have a lot of electricity storage in Denmark but we use sector coupling. We can use heat pumps in the district heating system to electrify the system and that is getting increasingly important. It's also economically viable. Direct storage of electricity is not used often because it is simply too expensive and not efficient. For demand side flexibility we are looking into different smart energy options. At the time being, there is no economic incentive to use it. If we will see changes in prices than it might become more attractive. There is a potential in demand side flexibility, but we will first try to couple different sectors such as heat and transportation. I think that we are already very well connected in Denmark to other countries so I believe that we have gained the most advantages of interconnections already. So, I'm not sure that it will be the most viable option in the future.

Critical materials

We have seen that prices of these materials went up in the history but prices have decreased again now. The wind turbines producers have become much more efficient in the use of these materials and I think that that is important. It seems at the time being that it is not a big problem but of course it might be a problem in the future but I'm not an expert on this. I believe that transformers of wind turbines are not produced in Denmark, they are produced in Germany or China I think.

Conflicts

I don't think there are specific issues that will be a source of conflict in the future. Again, I'm not an expert on this but I believe that each and every country has its own advantages in a renewable system. Some are going for biomass, some are going for solar and some are going for wind. It's quite distributed over the countries and we have an open trade so at the time being I don't see any problem. For example, with transmission capacity. If there is no mutual interest, you will not have this capacity development. We are a very small country so we cannot put a lot of pressure on Germany for example. I believe that if Germans are not interested in trading electricity with us, we wouldn't do it. Concerning cyber security, I don't think that a renewable system has higher cyber security risks. It is much worse if a large coal fired power plant fails than a single wind turbine, so as far as I can see it is more secure. But I'm not an expert on that.

Cooperation

I believe that renewables will lead to more cooperation. Openness is very important for trade and a mutual interest in trade. Furthermore, we should have some resources that we can trade so I believe countries should be different. It is good that one country has hydropower, one has wind power and, in that way, we can diversify the system.

Policy tools past

The tendering of wind power plants has been very important. Furthermore, we have set some strict targets that are very important. It has influence all over the energy sector. Strong targets have been very important.

Policy tools future

Wind turbines are going to be the base of energy supply in the future. The backbone of the Danish system is offshore wind. We need massive electrification of the system, for example by increasing the amount of heat pumps. We need better policy instruments for electric vehicles. We should try to less rely on biomass. The government should have an important role in achieving this. In the past we did not have a tax on biomass and we should have better certification on biomass now because it is not always sustainable. The government should use taxes to achieve the earlier mentioned things in a similar fashion as how they used taxes on electricity to increase the share of wind energy. We are lacking in economic instruments in my view, we should actually have common CO2 taxes on Danish level. In this, we should also take into account how we trade with other countries.

Future role of Denmark in the international energy field

We have had some impact on the EU level. Together with other countries we are aiming at the same direction so in that way I feel we are having some impact. A coalition of the green countries would be good. This coalition can than also push other countries.

<u>Interview 6</u>

Name: Pier Stapersma

Organization and function: Clingendael International Energy Programme, Senior Researcher

Date: 03-07-2020

General trends in the North European region

Growth of variable, incontrollable power, mainly wind and sun energy. Furthermore, the government is becoming increasingly important again. Investments are only done if state guarantees are granted. Different way of thinking as compared to liberalization in 1990's. Business have become executers of the government. Risks are socialised through public guarantees.

The governmental influence also affects foreign countries. In case of Denmark, the decisions made by the German government largely impact Denmark as well since Germany is much bigger compared to Denmark.

Import dependency of countries

Countries do not strive to as less import dependent as possible, but they strive towards a healthy balance. They want to find a balance between the lowest price countries and a certain level of security of supply (in times of crises). Being import independent is not overriding. In electricity systems, the concepts of net-importer and net-exporter differ. At certain moments, some countries are net-importers and at other moment they are net-exporters. It is much more dynamic. The fact that you are a net-exporter does not mean that you have not been dependent on import at crucial moments. So, Denmark has not become import dependent. The fact to which this should be considered as a problem totally depends on the trade partners. You have to trust your partners and in the Northern European countries, countries trust their neighbours in general. So it totally depends on the country. If Denmark would be Libya, the Netherlands wouldn't want to be dependent on imports of electricity from that country. It's not about the commodity, it's about the nature of your trade partner.
Denmark is a very small market that is very well integrated in a bigger market. Denmark is a statistical fault in the North-Western market. So everything they do can be compensated in the bigger integrated market. So hydropower in Norway plays an important role but the integration into the bigger system plays an even more important role.

Requirements for cooperation between countries

It starts with political stability of a country. In political instable countries, it is difficult to find good partners. Another important element in Europe is that the European market becomes less integrated in times of crisis. The covid crisis is a good example of this. If countries start the doubt whether other countries would treat their civilians in a similar fashion as their own citizens, than dependency can become uncomfortable. In times of economic prosperity countries want to trade and generate additional revenues through international trade. However, in times of limited availability of certain commodities, these trade flows might be interrupted. Therefore, countries might decide to invest in strategic reserves. The fact that there is a lot of trade between countries doesn't mean that they do not have strategic reserves.

Critical materials

Totally different debate. You should include this in another manner than the previously mentioned things. China has become the most important producer of rare earth materials. Western countries have a naïve idea that the world is a world of free trade, fair competition in which everything is possible. The world is however far more strategic. China is playing a certain game there but that is a totally different game than the one of energy security. Rare earths can be extracted in many more countries than only in China but not all countries do it because it is expensive and has negative environmental influences. Two developments that are important: technology producers invest in upstream or conclude contracts with private companies to create their own suppliers. So they are looking for alternative suppliers to reduce the risks of strategic games of China. Besides, there is awareness at governments, and they can for example subsidize mining or allow certain extraction activities. So, private companies are investing in these rare earths and a new balance is likely to arise. Another important question that should be asked is whether the growth process is not going too fast and whether extraction can be scaled up fast enough. Its more an economic question.

More or less conflict?
Be careful with simplification of narratives! It is a very complex problem. It sounds simple, oil and gas lead to conflicts so if we replace oil and gas, the conflicts are over. But it's not like that. Oil and gas can also lead to less conflicts because trade creates mutual dependency so you can more easily

attack each other if there is no trade. If certain countries stop trading with other countries, does that mean that economies will collapse? And lastly, do renewables lead to more conflict? I think that one of the aspects that might play a role of the fact that production of solar and wind energy requires a lot of space. Tensions might arise around the use of certain land areas. However, these issues are still far away so it is a very abstract debate. The more relevant questions have to do with the process, the shift from more oil and gas to renewables. Many economies will collapse because they are not able to change. The transition in itself is more interesting than the situation after. I think that the battle over power will not disappear simply because we have a new technology.

Role of European Union in the future

Forms of cooperation are important. Member States should work together on certain issues. Working together is important, especially on a regional level. The role of the European Union should be facilitating. They should help Member States to overcome certain barriers in the transition. It should, however, not become a European super state that fixes everything. European Union can also play a more important role on the world market. They can create European companies that have stronger positions in the world market and have power. Using this power can help to set up certain supply chains that are important for European markets.

<u>Interview 7</u>

Name: Ignacio Marti Perez
Organization and function: Technical University of Denmark, Head of Division Wind Energy Materials and Components, Expertise on research management and technology development
Date: 06-07-2020

Success factors in electricity system

- Strong interconnection of Denmark with neighboring countries and the connections of these countries through Nord Pool. The system itself is one of the key successful factors. In Spain for example, integration of wind was more challenging due to the limited interconnection with neighboring countries. More obstacles when you are weakly interconnected with your neighbors. Denmark has the advantage of a strong interconnected system.
- Profile of companies in Denmark, DONG energy and also the system operator, Energinet. These companies are crucial to facilitate the system. TSO is facilitating and enabling the transition. There are big players in the system who want to change and that is a strong signal for the market, for suppliers and also for governments. Strong support for the environment for many years. Cultural thing, environment was higher in Denmark for a green system as compared to other countries. Seen as opportunity for big companies, as a pioneer.
- The political situation in which wind energy was seen as opportunity. Stable environment. Long term thinking and focus on renewables. Not only for Denmark but also for other countries. It was an opportunity for pioneer companies.

Wind turbines vs fossil fuel power plants

Difference between those two types of power plants is to accept that you work with variable sources of energy and that you prepare the system to do that. In the beginning we said, we cannot operate the system with such high levels of variation. That was the perception. But it was a technical and cultural change to integrate these sources. Biggest change was to accept that we must operate the system in a different way and look where we are now. We are still in the transition phase now.

Export of know-how knowledge

The influence of the Danish industry on the offshore wind technology was big. Denmark showed leadership and was in front of the competition for many years. Besides, there have been exports of know-how knowledge from Denmark, for example to Spain. That was a key element of the beginning of offshore wind energy in Spain. That's another part of leadership. You start in Denmark, export it, and then the other country/company receives the technology and starts an industry as well. It's a good example of how Danish technological leadership can influence other countries.

Another key factor for success is strong connection between research and industry/companies. Development of industry and research, this strong interconnection is crucial. The stability of the research environment was important, that helped the industry. On both sides, you create links and knowledge is traveling two ways. This has been until now, the same culture still exists. Industry also guides research areas. From the side of the university, we are working with many countries in the world and that is another way to export know-how knowledge, through the research community. Examples are China, India, South America, Europe. In these countries our students and products are utilized and that is another way to show the link between Denmark and many other parts of the world.

Lastly, the government is also involved in cooperation. There is a very strong interconnection between the government, research and companies. When the government is taking initiatives, it affects industry and research. The government gives a stable message. In Denmark, not only the big companies are important for innovation but there are a lot of small companies influencing the supply chain as well. There are plenty of opportunities for these small companies.

Rare earth metals

This is one of the constraints. If you rely on particular materials it can be problematic. It is not only about having access to the materials themselves, but it is also about access to processing and the final product. When you have a problem like that, you do different things. You try to diversify but you also look whether you can use similar materials which are more common. Furthermore, research is done into the recycling potential. If it becomes a serious problem, the design would go into a different direction. Not all wind turbines need to use the same rare earths, there are different options as well. So, it is a compromise that needs to be made in the design.

Changes attributed to characteristics of wind energy

I don't know the exact origin of all of this. I think they changes are attributed to wind but also to other things. Wind energy is a sign of identity of Denmark. This is definitely one of the big areas in terms of export and industrial activities. On one hand you could see that people got used to wind energy as it grows. Wind energy is puling from Denmark as well. Wind energy is a global business now, so how to stay there? How to make sure you can keep having a frontrunner position? Wind energy is response for doing things different, that was the initial push that created this technology. Now that the technology is in the market, it also brings some new challenges to Denmark. It is part of the dynamic of the market, if you push to do something different you start employing something new. Wind is now so big and powerful that there are new challenges that you need to think about.

Strategy of government to help wind energy sector

It is obvious to me that it has been strategic thinking of the Danish government to say that wind energy is an important element of our portfolio. It has always been long term, strategic thinking. Then things have changed, as markets grew. Now there is a strong stable environment, there is access to funding in research, it is relatively easy to bring things in perspective. It is also the strong dialogue between research, government and industries. Good cooperation between the different institution.

Future challenges

The growth capacity of the sector is a challenge. If we see the objectives for CO2 reductions, we must speed up the manufacturing enormously. So yes, I think this is one of the biggest challenges. It is big because you need certainty before the investment in manufacturing are done. Companies need to sea the profitability and that is related to regulation. Furthermore, we should take into account the cost reduction and the huge competition in the market (tenders in the market). We need our companies to be profitable and to grow. They must to reduce costs very quickly but they also need to invest in manufacturing capacity. This is especially challenging when the market signals are changing. The Green Deal in EU is the kind of agreement that is needed for these kind of problems. The problem involves more than one country, it is bigger than that. We need size and stability and the role of Europe is crucial in that. It is a political message and many projects are European, not just Danish. EU should employ stable policy so that countries dare to invest.

Challenge of Denmark will be to deal more with sustainability. If we produce millions of wind turbines, we need to reduce the footprint of the manufacturing process of wind turbines. So less waste and less footprint. There is a lot of research in this area going on, the area is growing. Now that the technology is there, it is time to improve the technology from a sustainability perspective.

Resilience of energy and security of supply in terms of electricity is an important factor. The political implications to become less dependent on sources such as gas is also leading to new independencies. What is our dependence on the key components and suppliers? Not only on the materials but also, who is going to supply and maintain our wind turbines if we are going to rely mainly on wind turbines in the coming decades? It is not only materials and electricity, but it is also vessels to repair. It could be that you rely on particular equipment to access the wind turbines. There are new challenges that come with size. Our supply chain is ready for the size that we have now, but if we multiply by ten or twenty or more, what would be the implications then?

Interview 8

Name: Erik van der Vleuten
Organization and function: Technical University Eindhoven, Professor History of Technology
Date: 07-07-2020

Politics Denmark

A social democratic party Denmark is currently having power in Denmark and has a neoliberal agenda. This used to be different in the ‘70s when the conservatives and liberals were having power. They believed in central planning, they had a strong autarky feeling which has been an important reason that Denmark was trying to become self-sufficient. Furthermore, the oil crisis was an important reason for this as well. The liberal alliance and state alliance found each other in the energy crisis and the willingness to reduce import dependency, support of job opportunities. These goals led to the energy strategy of the Danish government on the wind industry and on natural gas from the North Sea. From then on, Denmark changed its policy and finally became an exporting country. Since the climate goals, Denmark is also trying to reduce oil. The Danish coal suppliers are quite steady countries. From the 1960s onwards, Nordic countries are cooperating on electricity via NORDEL and Eastern Denmark was also involved in ECPTE. Later, these cooperation mechanisms changed to ENTSO-E because of pressure from the EU.

For the geopolitical game, it is important to look into the interests of different countries. For Denmark it is important that the wind turbines market grows and keeps on growing. Denmark wants to guarantee a certain level of supply. Relevant questions in this debate are, what is the position of Denmark in the wind industry sector? What do we know about the Danish position within the climate negotiations?

One of the things that is important for Denmark is the relation with the Nordic countries. We can see that the Nordic countries have a strong focus on each other. This became also clear during the COVID-19 crisis. These countries were immediately opening up for each other while they were still closed for others.

Interview 9

Name: Ekaterina Moiseeva
Organization and function: Nord Pool, Market Monitoring Analyst
Date: 09-07-2020

Changes on electricity markets and prices

Power production became much more decentralized with higher share of wind power. Also, wind power production is volatile, which makes the import and export capabilities of Denmark important to keep the power balance. Power prices became more volatile. When there is a lot of wind available, power prices are very low or even negative. When wind power is limited – power prices are high. These changes are mostly associated with specifics of wind power – volatile production and low marginal costs/presence of support schemes. Since power markets are coupled, Denmark also to a certain extent depends on the price levels of its neighbours: e.g. northern Germany also has a significant wind power share, so often wind power peaks occur in both countries together, further pressing the prices down.

Electricity prices in different countries

The extent to which prices in different countries affect each other depends on transmission capacity available between the countries and the level of prices in neighbouring countries. The higher the number, the larger is amount of power under normal circumstances that can be transferred between two countries. It is also important to consider that different weather events have different effect on prices. For example, decrease or increase of wind power production is usually strongly reflected in Danish prices, since the share of wind power production is large. At the same time, a rainy day in Norway may only have a minor effect on Norwegian prices, since hydro reservoirs usually have large volumes and are sometimes not immediately affected. The economic theory points at advantages of market coupling, which is directly connected to price dependencies, in terms of total social welfare. In fact, interdependencies often help the stability of power prices in domestic market.

Interstate cooperation on the electricity market

It is important that the market design is compatible (currently ensured by EU-level regulation) and that support schemes or political agreements in different countries do not distort the market.

Future with higher wind shares

A larger wind share creates volatility in prices that may mean higher dependency on import and export capabilities to other Nordic countries/Germany. It is beneficial if further increase of wind energy share is based on the wider market situation, i.e. if price signals from the market play a role in how investments are decided. The increase of wind energy share also needs to be accompanied by proper grid development and a plan for ensuring the security of supply. Concerning trade between countries, more interconnectors result in more cross-border trading if price differences occur between countries.

<u>Interview 10</u>
Name: Bo Riisgaard Pedersen
Organization and function: Danish Consulate Sillicon Valley, Energy attaché
Date: 10-07-2020

Changes in electricity market

In the late 1980s we had a very centralized power grid. We had relatively big power plants located close to the sea and located close to the border because they needed cooling water. In the early 1980's two things happened: we started extracting natural gas in North sea and construct gas pipes to transport the gas throughout the country. Gas needed to be used in the most social viable way. Energy planning was important during that time. During the '90s more decentralized power generation plants were constructed. The first initial focus was, it all boils down to the energy crisis. In the 90s the climate topic started and we needed to do something on the green agenda. Wind turbines had already started then but then more efforts were done to increase them. Now, the first three offshore parks had a single connection point so they send their power to a single onshore point and they have characteristics of big centralized power plant. But now, Energinet has wind parks that have more connections from which the energy can be distributed to different actors. Only a few parks that have the characteristics of a centralized system.

Denmark as transit country

Denmark is a transit country that can easily transport electricity to the Nordic countries but also to the Continent. The number of electricity traffic between Norway and Germany that flows through Denmark is very high. Especially the western part is a transit country. When we have a high share of wind that is difficult to predict, it is really convenient to have pumped hydro in Norway and to be able to sell to Germany. So I think there are no major implications, it just means that electricity flows to the market in which it has the highest value. With the Netherlands, we have the cobra Cable, that is also to sell to markets with higher prices. So it is really a market thing. The Nordic market, really works, it just makes sense. It is going to get more tricky when you increase the share of wind. The interconnectors in Europe are then the way to go.

Import dependency

The dependency from Denmark on other countries to maintain grid stability is not problematic. Again, it's a market thing. If it becomes problematic, the prices will go up. So, energy security is good, but it it is still a local resource and you would still supply to local markets if the price is higher because you have transit costs, transportation losses. So you will sell it in the local market if the demand is there. What could happen: Lets imagine that the UK is going to produce more electricity than they can consume themselves and it is going to be extremely cheap and Denmark will import a lot. And for if for example the UK would stop exporting, than the difference is that the resource is local. We would still have wind energy that we can produce. The interconnector is just a way to always offset the electricity. The more markets you have access to, the better. My opinion is that investors will be looking for countries that have good highways so that they can sell electricity to other markets.

The interconnectors also have the aim to maintain flexibility in the grid. But their role is two-sided: they are used to generate revenues and to provide flexibility, they go hand in hand. If you have stability on your grid, you are able to start to generate revenues. Its not the MW that dictates the market. Tricky because if the amount of fluctuations increases. Until now, we have been able to maintain back-up and technically adjust the system. There are different tools that can be used for grid stability, now we have used all the tools technically and now we should make sure that we used the market. A very technical problem is related to intertia. We might loose reaction time of the system so that the TSO receives signals too late. This might affect the market model as well, so you need different solutions and only the future can tell to what extent it will be a problem. It is very technical but it is an important part because the physics will affect the market model and international trade and also geopolitics. Basically, if the market model reflects the physical world, then you won't have a disconnect between grid stability and possibility for revenue generation.

Critical materials

We need steel to build turbines and we don't have steel in Denmark so we are very dependent on getting steel. I think what we will see is that Denmark will continue to build out offshore but onshore we are replacing 10 old turbines by 1 new one. We are building out, generation wise but we are not going to increase the amount of turbines. But to my knowledge we cannot reuse all the old steel so we are definitely going to need steel. For that, we depend heavily on the EU.

Then we have glass fiber, but I don't know enough about that. Then, we have power electronics for which we are cooperation with Germany who provide it and the knowledge is based in Denmark. We see that other companies come to Denmark because knowledge is there. We attract a lot of talent from EU to Denmark because it is a Hub. They might learn something and go back, Spain for example. We will be a hub for offshore. Another interesting thing to see is when we move to floating offshore. The potential is very huge. The next level is to make sure your grid is stable. We can export ideas on energy storage, how do you run a grid with fluctuating generation and the power to X is something Denmark is hoping to be leading in. So, the knowledge on the system around the turbine is a major exporting product. It is hard for me to see any geopolitical issues on that.

Renewables and cooperation

City of Esbjerg, used to be an oil and gas town. A large degree of the build out in the North Sea ships out from that port. It doesn't make sense, economically, to have a port both in Germany, Denmark, the Netherlands and the UK. But a port creates a lot of jobs. So you already see that there is a lot of cooperation going on when it comes to arranging. For example, Denmark has a port, Germany has some vital components. When we move along the supply chain of offshore wind, we see a lot more cooperation between EU member states than in States in the US. As long as we all get a share of the pie, its fine to work together. It seems like we have a very good inter European cooperation on this topic. I would say we see more cooperation, also because of the energy islands. Even with the Netherlands, who is partly subsidizing Danish PtX. The Eastern shore of the US is fighting on these topics. Every State wants their own port, 3their own manufacturing facilities. The European countries are telling the US, you have to cooperate. You cannot do everything by yourself. But there is a much bigger focus on jobs there so it's a different way of thinking. They do not have the same tradition for cooperation. In Europe, countries cooperate because they see that there is a market, they see it as an opportunity and they are also driven by green, cheap electricity.

Good cooperation is very important! Not only on TSO level but also on the ministry level.

Strategy to reap benefits of transition

One of the major issues is the agreement on energy policies and the consensus among parliament. Politicians were able to agree on energy topics and create long agreements. As investor, this also gives a lot of trust and certainty.

Current challenge

The biggest challenge is in the transportation sector, wind turbines can be part of solution. Looking from a system perspective, we fixed the electricity sector. Issue are now in other sectors.

<u>Interview 11</u>
Name: Mary Thorogood
Organization and function: MHI Vestas Offshore wind, Senior Specialist and Business Development in new market
Date: 13-07-2020

Difference fossil fuels plants and wind turbines

Managing variable nature of power onto the grid is the most important difference between wind energy systems and fossil fuel based systems. We see in other parts of the world that countries struggle with cooperation on this. For example in Asia, countries are not used to cooperation with neighbouring countries. This is similar in the USA, where states are neither used to cooperate. All these countries want their own manufacturers rather than working together. This will probably the same in South America. The other difference is the issue of permitting. For example, land-based permitting at sea. How to work with other ocean users?

Players in wind turbine sector and Danish role

Northern European operators are important players in the market. Important players are the three turbines manufacturers, cables, foundation, towers, blades, for electronics in the turbines, smaller manufacturers. All of these items are mainly concentrated in Northern Europe, especially in Germany, Denmark, the Netherlands but also Spain. Main components come from Northern Europe but also increasingly from Asia Pacific since we started there. We have a partner in Taiwan for example, who is building the blades. It makes sense to have more developers in the region where you want to produce.

Denmark has a lot of know how in the supply chain. Not just turbines but also other components. That is a business that will go to new markets and that they can export. Another thing is the ecosystem of the Danish Energy Agency, the embassies and how Denmark sells wind industry abroad. Not only in terms of wind turbines and components but also that it is very aligned with the other policy goals of driving decarbonization in the emerging economy. I think it is a list of 15 markets where they do offshore wind and that is what helps to take the wind industry to the next level for Denmark. They use embassies and ambassadors to trade. They use existing connections but they are also very good in building new ones. Denmark also sees this as an opportunity to gain influence. Denmark really pushes above its weights for a very small country on energy policy. What they do is targeted, they pick their areas and that is what they do.

Rare earth metals

We do use these rare earth metals but better to look into the sustainability report of Vestas about supply chain. It is not particularly seen as a significant problem. Vestas does a lot in engineering to minimize the use of these materials in our turbines.

Growth capacity of wind turbine sector

I don't really see the growth capacity (in terms of available ports, vessels etc.) as a problem. Our supply chain is organized on a regional basis. Because it does not make sense to export everything from Northern Europe to the rest of the world but it also does not make sense that every country creates its own supply chain. I would see growth at being limited. If we look at what wind will go to, the supply chain will be able to supply that. You might see limitations on vessels in the coming years but I think that the supply chain will meet the market. It's a huge business opportunity. So I wouldn't say growth is limited.

Requirements for regional cooperation

Transparent and open dialogue are important requirements. Furthermore, the recognition that different markets have different strengths. For example, the UK is very good at servicing turbines so it is about understanding the different capabilities, then everyone can win rather than thinking it can all go to one place.

Attributed to characteristics of wind

I think there are other factors, every market has its own context. The energy islands are a good example in the coming years in which countries in the Nordic sea are going to cooperate. That is driven by wind, but it is also driven by Poland wanting to be more energy independent than it is today. And it also wants Danish help in achieving the climate targets. Wind can be part of the story but I don't know whether it is the main driver. Energy independence could be another important driver. And also economic benefits. Two countries cooperating can drive something better for both countries. For example, if countries agree to share training.

Policy tools used by the Danish government to achieve today's position

The Danish government has a clear line of sight of what they wanted to achieve with offshore wind. They had a clear ambition and they did what they said. That makes Denmark investible for all developers. The Danish new energy plan is also very ambitious. The main challenge will be to deliver the energy islands in time, 2025 is almost tomorrow.

Additional topics

The relation between China and EU on steel. We use so much steel in our turbines so the free trade between China and the EU and other far eastern countries is very important. Challenge for Vestas as well.

Interview 12

Name: Anonymous 3
Organization and function: -
Date: 21-07-2020

Goals of European cooperation

- Greening of the energy system. This process involves a huge change and it is totally different as compared to how we have structured our system thus far, also for stability and security of supply. For example, we become more dependent on the weather and therewith we also have to accept that we become to a certain extent more import dependent in situations when there is no wind. We can increase capacity of our turbines, but as long as there is no wind, we still need to import from neighbouring countries. So, increasing the share of wind, also means accepting that you have to import at certain moments. That is a largely political question. Is it okay for us to accept that we depend on other countries? Furthermore, we also need to look how we can safeguard this stability domestically for example by offering flexibility mechanisms.
- Integrated electricity market. At the EU level there is this bigger picture of an integrated electricity market that countries strive to. The more interconnection, the more stable the system and the lower the electricity prices. These are basic market rules that can be applied to the electricity system as well. Cooperation between countries is something that perfectly fits within this picture.
- Opportunity to generate revenues. What opportunities are there to become frontrunner in the transition? Countries look into the specific role that they can play in the wind energy sector on a global level. In Europe, we have conversations on moving the supply chain to European ground. In the future, obligations might be developed to ensure that turbines are developed on European level.

Export dependency?

The fact that countries are exporting in order to maintain grid stability is not necessarily problematic for energy security. It is merely a problem for the business case of wind. If you cannot export wind to neighbouring countries anymore, you can just curtail production of wind turbines. The problem is, however, that curtailment is not economically viable because you lose electricity. In my opinion, export to other countries should not be seen as a dependency. It is, however, important that we create more alternatives to do something with the electricity. We must ensure that we do not lost electricity but use it in a beneficial way.

Conflict or cooperation?

The scale is important for the conflict issue. Within the EU, wind energy mainly induces cooperation between countries. It creates a sort of unity of the system. For example, between countries around the North Sea. Cooperation projects are being developed, not only to collaborate on wind energy production but also on hydrogen, electrolysers and the amount of interconnectors. These all-encompassing forms of cooperation are also more solid than cooperation on wind only. They induce flexibility in the system and reduce uncertainty. On the other hand, if for example hydrogen is going to play an increasingly important role in the future, it might be possible that we need to import it from other places. The EU does not have enough capacity to generate hydrogen to foresee the whole continent. We might then be forced to import it from North Africa and its solar parks. I can imagine that conflicts within these regions evolve around land use; who is going to own this ground and the produced hydrogen. However, it is still far away. We might have more insights in these kind of tensions in ten years.

Interview 13
Name: Aidan Cronin
Organization and function: Siemens, Advisory Specialist Wind Power
Date: 23-07-2020

Countries involved in supply chain of wind

Denmark, Germany and the Netherlands are all big players. The Netherlands is one of primary hubs for offshore technologies. Blades are constructed almost everywhere, towers are often imported from Vietnam. Big wind energy companies are getting together. There is a huge collaboration between the companies active in this field. Collaboration can optimize the volume of components, lead to lower price and higher quality. In 80's there were 90 companies but consolidated in less companies. International competition has become more brutal. In the end it settles down with two or three European companies and two or three Chinese companies. Denmark leads the critical mass. Denmark had a huge advantage in the past, mainly because of the critical mass, but also because of stable policy measures and the fact that knowledge was here. Design of wind turbines is now more international. It became quite a global thing, Vestas got into offshore. Vestas shared a lot of experience, which gave Denmark huge position in wind.

Trade dependencies between countries

An important example of dependencies is the Dutch offshore wind installation fleet. Without this Dutch offshore installation fleet, we couldn't do what we do now. Dutch installation is very huge, it became a niche for doing offshore. This is not problematic, the relations are based on confidence. Wind energy is a heavy industry meaning that the quality is very important. You always try to get the best because you want it to last for a long time. Therefore, companies just import what has the best quality.

Critical materials

We have neodymiom almost everywhere. Especially since China delivers 80 percent. Industry is trying to reduce the use of critical materials constantly, there is a huge drive in market to reduce and get rid of them in the end. Discussion on rare earths, we are big users but if you look at the Baltic, they have them as well. The wind industry is actually quite good at it or at least within a year, for example by recycling them. Off course it is a concern but I don't see it as a major problem. But there is no doubt that a lot needs to be done. On a European level, countries are working together on this issues but there are also countries that say, we do it ourselves. It is not an easy issue, there is a lot of politics and strategy involved.

Conflict vs cooperation

In EU, there will be a huge form of cooperation. The idea is to have a European grid. It helps to have a long term planning. If everyone agrees, it can contribute to cooperation between countries. For example, the gas pipeline system. That is a fantastic example of good cooperation between countries. That system is much better integrated than the electricity system. The problem is however, that electricity, and wind in particular, is such a small part of the total energy system. I believe that wind worldwide is only 2,9% of the total energy use. So Denmark is big in wind but very small in energy. It should therefore ask itself how to get into the energy market.

Most important challenge

The biggest challenge for Denmark is to stay relevant. Wind is a very mature technology. As soon as countries have adapted it, out frontrunner position might go away. We should look into new markets. For example, the ammonia market is going to be very big.

Additional things relevant for research

The aging of Europe is something that might be important as well. The population is more conservative because of aging. There is huge disconnect between the older and younger generation. We have seen this in the US but also in the UK for example.

Interview 14
Name: Peter Markussen
Organization and function: Energinet, CEO Associated Activities
Date: 23-07-2020

Strategic reserves

There are two types of critical situations. The first is when there is no wind while you need capacity and the second is when there is a lot of wind and you need to export it. The later can be dealt with by turning off production units but that's not good for the business case. To deal with the vulnerabilities, Denmark has not yet strategic reserves. There are of course reserves that can be used when the system has an outage. For example, if the largest entity in the system has an outage, then you will be able to replace it in 30 minutes. We buy 700 MW reserves. Buy them in DK1 or DK2.

The question is now whether we need strategic reserves in the future? We have a target for Security of Supply and to be able to fulfil this we might need strategic reserves. It depends on how you look at the future. We might need strategic reserve but at the moment it is not very necessary.

Denmark as transit country

Denmark is a transit country between the continent and the Nordics. On the one hand, this is an advantage, because Denmark can benefit from cheap electricity prices in Norway and Sweden and in Germany and can also sell this electricity to the other countries for a higher price. Denmark is, however, also vulnerable in this position. If we import but are not able to export than it is a risk, or the other way around, if we export but not able to import, we have a problem. You can describe this as a bath tub problem. An example is that Tennet has reduced capacity on the Danish German border, that is problematic for us. Furthermore, there are some problems on the connection between Denmark and Norway which creates some challenges as well.

Dependency on neighboring countries

Denmark is very dependent on its neighbors. However, we don't consider this as a problem. That is different from for example TenneT in the Netherlands and Germany, they see this dependency more as a challenge. We used to see it as challenge as well, but now all countries have experienced the social economic benefits so its considered as an advantage. We can help each other. That's also a reason why we don't have a strategic reserve, we can always import or export electricity. The fact that we have the European Union also created a kind of legal foundation for the cooperation. If there are any problems, the EU can interrupt. Furthermore, this legal foundation is also important for politicians because they can use that in their argumentation.

In 2010, there was a problem between Eastern Denmark and Sweden. Denmark wanted to secure free flow of electricity and transparent price setting according to the EU electricity market directive and the EU was involved as regulatory authority for the implementation of the directives.

Organization of trade

Trade between countries started with bilateral agreements between two countries. After that, the Nord Pool was created which was owned by TSOs from different countries. This is arranged through multiple agreements. After that, the EU created the European electricity market. Now we have full market coupling 2018. Still, most of the trade is based on market mechanisms. More than 90% of the electricity is traded via Nord Pool. The Cobra cable between the Netherlands and Denmark is part of the EU market coupling. So, in the first place we didn't need the EU for cooperation but if there are certain problems or tensions now, for example at the German and Danish border, it is good that the EU can intervene.

Conflict vs cooperation

From a Nordic point of view more wind has definitely led to more cooperation. This collaboration is still getting closer and closer in electricity system. Towards the continental EU it is still a question whether they will cooperate more. On the one hand, there are the socio-economic benefits, but on the other hand countries have a more national tendency. For example, Belgium used to have very high electricity prices for a certain period. Other countries learned from that, in the way that they help each other on system management. The reason why cooperation works so well in the Nordics is that we supplement each other. Norway and Sweden have hydro and we have wind.

Future challenges

Most of the interconnectors are more than 20 years old so we must reinvest in them to maintain enough capacity. For example, Norway is also constructing pipelines to the UK and Germany so the question is whether they then still need so much transmission capacity to Denmark. In making this decision security of supply and socio-economic benefits are the most important variables to include. Another strategic question of Denmark is; are we going to export our cheap wind electricity or are we going to use it by ourselves for example in market coupling or to create hydrogen. What strategy do you chose?

Overcoming future challenges

Three things:

1. Support EU development of electricity markets and system operation
2. Maintain good relations to our neighbours and try to create a set up of the system in which socio-economic benefits are created for everyone

3. Sector coupling, creating new opportunities to integrate more electricity into the whole energy system

Interview 15
Name: Eize de Vries
Organization and function: Windpower Monthly, Technology and market trend consultant
Date: 29-07-2020

Danish position in international playfield

Denmark has a very strong position in the wind energy sector. Big companies such as MHI Vestas are Danish (also partly Japanese). Furthermore, Denmark has many knowledge institutions, engineering firms, a technical university. So, despite Denmark's small size, they play a very important role in the industry. Denmark is also trying to gain market share in countries where wind is not big yet. They help these countries by sharing knowledge.

Critical materials

Offshore wind turbines of, for example, Siemens Gamesa use of lot of critical materials, so these companies definitely depend on those materials. China has the largest share in the market, mainly because they have the lowest environmental and health requirements in the mining process. More severe requirements in other countries make those materials less competitive. So yes, critical materials are something that companies take into account. They try, for example, to spread the supply chain over different countries. In 2010, there was a strong price increase and therefore companies tried to decrease the use of critical materials. At the moment, prices are, however, normal again so demand is at the old level as well. I think that companies take the risk of critical materials into account but when it forms a true risk, they will stop constructing installations that need these materials. Companies and governments are trying to decrease the risks by looking for alternative materials that can be used and they are finding ways to recycle the critical earths. The same accounts for steal. An enormous amount of steel is needed to construct monopiles. At the moment, steal is not scarce so it doesn't form a problem.

Conflict or cooperation?

I think that the decrease of demand for fossil fuels is the most important form of conflict. Countries such as Saudi Arabia and Russia that heavily rely on income from these sources have a problem if demand decreases. Stability of country might be affected if they lose a significant part of their income. Countries with a lot of oil or gas worry about the energy transition. Concerning cooperation, I think that renewables can also be a form of collaboration between countries. Professor Gijs van Kuijk, talked about an integrated electricity network between countries that are bordering the North Sea. A big park might be built, which can export electricity to the UK but also to the Netherlands. A wind park like that is something that can give countries a lot of advantage. Connecting countries is helpful, countries experience advantages through cooperation.

Cooperation on the supply chain of wind turbines differs per country. Some countries try to localise production. For example, in Taiwan, governments create production targets of components that need to be produced domestically. Localising the supply chain creates job opportunities and helps national economies to grow. Especially for developing countries, internalising industries can have a lot of advantages. For countries such as the Netherlands, origin of the components of wind turbines is less important. Long distance transportation of wind turbines is, however, not efficient since these products are enormous. This might also play a role. Besides, the corona crisis has also made countries more aware of the origin of their products. For example, the great dependency on mouth masks made countries wonder to what extent they want to rely on other countries for certain products. The same applies to the ongoing trade war between the US and China. That war makes countries aware of the fact that they can be very vulnerable if they depend on one single country for supply of certain materials. It is, however, very difficult to estimate what the future will bring. We just have to wait.

The Netherlands

In order to obtain a similar position as Denmark, the Netherlands should use its favourable position. For example, by making the harbours suitable for loading and unloading heavy products. The Netherlands is already very fgood at installing wind turbines. There is a saying which says that the Germans and the Danish supply the products for wind turbines, the Dutch install them and the English drink tea. Furthermore, it is very important to have a long-term vision. Huge amounts of investments are needed for which a clear vision is essential.

<u>Interview 16</u>
Name: Morten Pindstrup
Organization and function: Energinet, International Chief Engineer
Date: 30-07-2020

Denmark as a transit country

Yes, I would characterize Denmark as a transit country. The Western part of Denmark is connected to Norway, Sweden, Germany and the Netherlands and the Eastern part to Sweden and Germany. In 1990, we had a system with two large power flows twice a day in the Western part. At night, power was flowing from Germany to Norway, than at 6 in the morning, power from Norway to Germany. Reason for this is the way in which operators were offering electricity and trying to optimize costs. When demand went up in the morning, the Norwegian operator could make more money and the demand would go up and price down, so there was a power flow to Germany. So, the electricity flow was switching all the time. At that time, it was very clear that Denmark was a transit country. This position continued, but to a lesser extent. Now that we have more renewables, wind decides how the power flows. In periods with sufficient water and no wind, we have a similar situation as in 1990. When there is a lot of wind, excess wind determines where power is flowing to. Often, countries end up with same price because of the strong connection between Germany and Western Denmark.

Barriers to entry or exit the Danish electricity market

Denmark has low barriers to enter the market. We have had quite a lot of new entrants because renewables are so cheap. We have tried to simplify the rules and try to make it as accessible as possible for generators to enter. We need many generators to increase competition. Denmark is a small market so one would expect a small amount of market participants. As a generator, you can call PPA (power purchasing authority), to who you can sell your electricity. If you comply with grid requirements, you can start generating. We have 43 PPA's in Denmark and they are in competition about handling new generators. It has become easier and we see more new generators than we have for quite a long time.

Strategic reserves

Denmark doesn't really have the possibility to always be able to deliver electricity to its consumers. It is possible that a situation could arise in which all interconnectors were closed. We could then have hours in which we don't have electricity available for our consumers. But the fact that we have these interconnectors means that we trust in them. Some of them will be always able for use. And if there is for example stress in Germany and Denmark, we are still able to import from the Nordics. So, we do believe that we need to help each other if a certain country faces problems. This is, however, not as firmly established in electricity system as it is in gas system. In gas system, it is better regulated that countries help each other, sharing of the burden is more clear. In order to improve cooperation, we have regional coordination centers throughout Europe. These centers help by doing security analysis in regional context. Countries can get a better understanding of what is happening in a larger area. This helps countries in their decision-making process and gives them more certainty. It is less likely to face problems if we help each other out.

The fact that Denmark doesn't have a strategic reserve has been a discussion for a long time. We use stochastic modeling techniques to outline the situation in the coming 5 or 10 years. These techniques help us to outline whether or not we will have shortages. Thus far, strategic reserves have not been necessary, but we might need them in the future. So countries can ask themselves the question whether they are able to supply themselves at any moment in time, but in an integrated market that might not be the right question. Furthermore, as long as we keep subsidizing all kind of things in the electricity system we will not have a normal market situation since we don't have price spikes. There is no easy way to get out of this because of the green transition, we also need subsidies.

Unavailability of interconnector capacity

There is a chance that certain interconnector capacity that is available at the moment, will not be available in the future anymore. That is definitely a risk for Denmark. Specified to the border of Denmark and Norway, we now have 4 interconnectors of which 2 are quite old and need reinvestment in the next decade. So that decision must be made in the coming years. There is a chance that Norway finds it less interesting to invest in these interconnectors because they are also expanding capacity to other countries. We cannot say yet what decision Norway is going to make but it is an obvious risk for Denmark. For Denmark it is definitely better to have more capacity than less, because of stability in power prices in general, and because it helps to balance the market. There is, however, no specific strategy used to deal with this risk. Generally, we deal with these kind of issues case by case.

Organization of trade relation

How this is organized has changed over the years. It used to be organized via bilateral contracts. Nord Pool published how much of consumption is traded via Nord Pool. In Denmark, this is 95% and in Norway it is 100%. So, trade through power exchange is the easiest way. Also because everyone knows that it is a fair price that is offered at the power exchange market. These power exchanges don't have monopolies anymore. There are power exchanges almost everywhere.

Potential forms of conflict

There is no single answer to this question but between countries, there are things that are not ideal. When we build renewables we tend to build generation further away from consumers. When we do so we connect the generation assets to the nearest set of transmission that we have since we try to limit the amount of resources that we need for construction of pipelines. Often, this connection point is also very close to the neighboring countries, taking capacity of the line of interconnector. Since the capacity can only be used once, the question becomes: what do I prioritize? Subsidizing my own wind, or import it from my neighbors? The last time, countries tend to give priority to internal wind. So, conflict might arise between member states and their push for renewables and the EU legislation which requires something else, namely that countries always have a certain amount of available transmission capacity. That conflict, (its not war) can be quite contentious. No one want wind parks in their backyard so we have to build them far from the consumption location. This can create conflicts between member states and we need a reasonable way of handling this. A possible solution could be that we create large North Sea wind farms that are owned or financed by all countries. Not only countries around the North Sea but also other countries that pay can get CO2 credits for it.

To some extent, the EU works as a mediator in these kinds of conflicts. But in some way, overall efficiency of system, what the EU wants, can also create conflict between certain countries because they might feel that they do not get the same as other countries. But on the larger scale, the integrated electricity market could not happen without some sort of EU government and mediation.

Interview 17
Name: Thomas Egebo
Organization and function: Energinet, CEO and President
Date: 04-08-2020

Main dimensions of geopolitical implications

- **Electricity itself**. The question is: has all the wind affected our approach to the electricity system? It has, in the sense that we realised that having a lot variable energy production in the system proposes some challenges. These challenges are partly solved by the use of interconnectors. We have interconnector lines to NL and are also building a new connection to the UK. Quite early on, moving into wind had led to the fact that Denmark became a spokes country in terms of EU integration and common rules. Denmark is blessed with good neighbours. We have a mutual perspective on the electricity system. Norway had water, but they are in trouble if they have a dry year, so everyone benefits from integration.
- **Early movement into wind has add on manufacturing and energy businesses in Denmark.** Specialization in wind energy has led to Danish exports of components related to the energy sector. Two examples are the energy companies Vestas and Orsted. These companies gained value and became very successful. The movement into wind energy has had impact on competition on an international level as well. It increased competition. Denmark has good conditions and to become successful, we already had some knowledge and test sides were available as well. The wind industry grew up here. Orsted, the company itself, decided to go green. It grew from an oil and gas company and had conventional power plants converted into biomass. The company gained experience with offshore wind farms and was amongst the first companies in the world. Hence, it became a very experienced player in offshore business. Why did the company decide to go green? It realized that politicians meant the 'going green thing' seriously. Therefore, it started to look into wind and ended up having quite a good business model with which the company was able to earn money. So their transition was partly driven by the assessment that eventually things would become 100 percent green and because they were able to earn money. Other major energy companies have gradually moved into offshore wind industry.
- **Foreign policy, a geopolitical kind of dimension.** Denmark is a relatively small country, which has not a lot of global influence. The energy area is, however, an area in which Denmark has influence. An example of that is that ambassadors want to look into energy because they see it as a form of cooperation in foreign countries. The energy sector creates the ability to open doors to other countries thanks to the extensive Danish experience. This is also part of the foreign Danish policy. The country therefore actively seeks cooperation with other countries on energy questions. There are, for example, various cooperation programmes on themes related to energy. The government tries to actively do this. One reason is to gain geopolitical influence, but another reason is also because the Danish government strives towards a green world. An example of a foreign cooperation initiative is with China. In this programme, Denmark helps China to reduce wind curtailment. These kinds of programmes help to reduce emissions. If China for example, could reduce its curtailment with 15 percent and integrate this green electricity into the system, the effect is already very big.

Denmark as transit country

The fact that Denmark is a transit country has contributed to the ability for Denmark excel in the wind power market. When wind was much smaller, we were already very well connected with our neighbors, so trade of electricity was easy. This trade was mainly market based and based on relative prices. This market set-up already existed already a lot of years ago. So, we had a system which could absorb a lot of wind. Being the transit country was beneficial for the integration of wind power.

Strategic reserves

We do not have strategic reserves but we have a few power plants left, and we have interconnectors. Between Denmark and Norway, we already have 4 transmission lines and also with Sweden and Germany we have multiple transmission lines. So unless everybody cuts-off these lines, we are still able to import and export. As long as the market functions, it does a great job in security of supply. But off course there are still challenges. If we want to go to 100% renewables, we have to develop new solutions and technologies, digitalize electricity system and provide small sources of flexibility.

Changes attributed to characteristics of wind

Looking at electricity strictly speaking, the need for more interconnectors and trade can to a large extent be attributed to wind. But not solely to wind, there are economic reasons as well. The relations in the two other dimensions (as distinguished in Q1) are not necessarily related to wind. They are more related to being the first mover in a new technology. The fact that we moved into wind, resulted in the growth of certain industries. These industries have some international and geopolitical influence.

Conflict

No conflict, one good aspect of wind and solar is that it is available, so you don’t need to start a war to control it. So, there is no need to control certain areas to secure supply. Wind and solar can be extracted on a smaller scale. You need a kind of cooperation for integration of these sources into the electricity system.

Cross-border tensions

Cross-border tensions could happen. It takes a long time to build up infrastructure, so it also takes many years to get rid of it. In the Northern part of Germany there is a bottleneck which could be solved by dividing Germany into two price zones. These sorts of tensions will always be there. It’s not always easy to set up infrastructure, some countries are, for example, struggling to get the permits they need to expand the grid. But this will not lead to huge conflicts, also because there are sets of rules in EU energy market. In the end, it is an advantage for all of us to have a more integrated market. It takes some years to build a true energy union. Countries have differences but hopefully in the end everybody will realize that going green also means going into direction of cooperation.

Cyber security

Cyber security is a growing focus. The question is whether it would be less if we would have a very decentralized system. The system is never stronger than its weakest links. Cyber security is becoming a bigger threat. In general, it is becoming a bigger threat for almost all sectors but if you would make a list of top 10 industries that are mostly affected, energy would definitely be on the list.

Strategy to reap benefits of transition

The most important strategy to reap benefits of the transition was staying in the front, among those countries that are most ambitious. Denmark keeps on pushing development in the industry and the fact that the government is very ambitious climate is also reflected in the energy sector. Denmark is always trying to develop new solutions. An example in wind is that the government is currently looking into the possibility of having energy islands. Connecting individual offshore farms is more expensive than having one island. If you really want to become big in the offshore industry, you need these kinds of islands. The government is supporting this development through research, innovation, test-facilities, and their impact on green industry. The Danish government is well aware of the fact that being ambitious has some benefits for the economy.

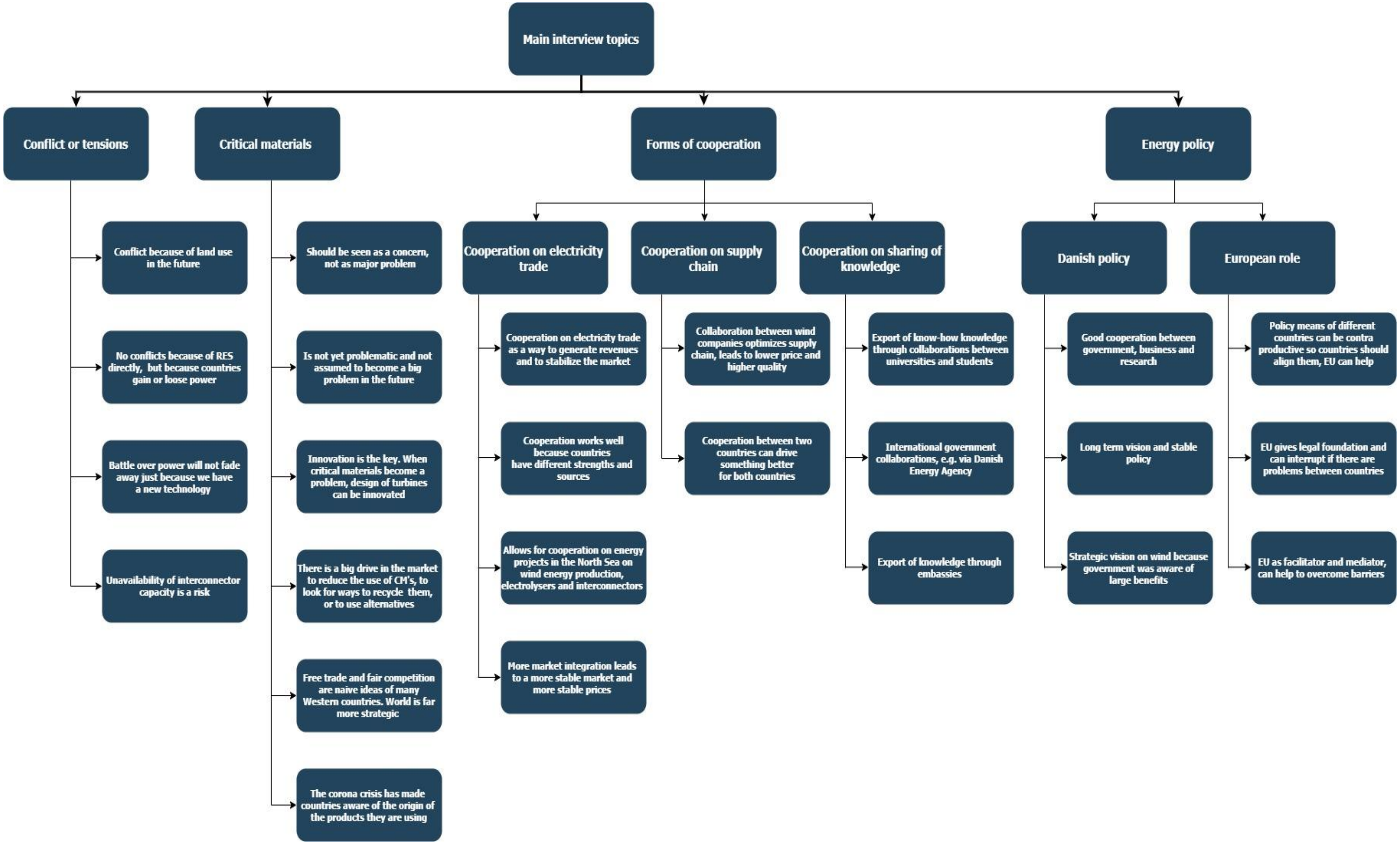
Geopolitical challenge

Energy moves along borders, not only country borders but also borders in sectors and borders in time. The challenge is to be able to develop a kind of super flexibility which enables energy to move more freely. There are currently already some developments in batteries, Power to Gas, and hydrogen based systems, which convert wind into hydrogen as building block for green fuels. If this could work, it would be perfect. The reason that there currently is a large focus on this is because people have realized that if you want to go 100 percent green, you need it. The options are not viable yet but it will be an interesting area for the next years, companies should do investments and governments should ensure a strong and stable regulatory area. Cooperation is important here as well, mainly through EU associations.

Appendix C Matrix with outcomes of the interviews

	Cooperation			Critical materials	Import dependency	Conflict	Policy (EU or national)
	Supply chain wind turbines	Knowledge	Electricity trade				
Business	In Northern Europe we see cooperation on the supply chain of wind turbines, but that's not the same everywhere in the world. Cooperation can be beneficial for optimization of the supply chain.	Denmark is actively exporting knowledge to take the wind industry to next level and gain market share in foreign countries.	Cooperation on EU grid network helps to stabilize the market and contribute to well-functioning market	Critical materials form a concern but not a major risk. If it becomes a true risk, there are options such as recycling or minimize the use of those materials.			
Governmental organizations		Denmark is cooperating through knowledge sharing and energy questions. Not only knowledge on wind turbines but also on the system around wind is a major export product.	Interconnectors help to stabilize the market in terms of electricity prices and market balance. Furthermore, they support electricity flowing to market with highest value.		Import dependency is a rather political question; is it ok to accept the risks? For Denmark it's no problem because of good relations with neighbours and complementing sources.	Conflict might arise because countries gain or lose power or on the availability of transmission capacity.	The EU can work as a mediator, interrupt when there are problems and create a legal foundation for cooperation.
Research				Critical materials are no big problem yet. If it becomes a serious problem, there are alternatives: governments can invest in upstream mining, allow for extraction or design of turbines is changed.	Whether import dependency is problematic or not largely depends on the nature of trade partners. For Denmark not problematic because dependency is mutual and there is trust.	Conflict is not seen as a major concern. Land use issues or cyber security might lead to tensions. It is a difficult topic, be careful for simplification of narratives.	

Appendix D Code tree interviews



Appendix E Rationale for variable selection

Geographical, technical and economic characteristics			
Component	**Variable from** Scholten (2018)	**Adapted variable in this study**	**Rationale for leaving out/adding variables**
Source	Geographic location		
	Stability/Variability		
	Overall potential in meeting demand	Generation potential	Potential in meeting demand depends on a large variety of aspects. One of the important aspects is the on land geographical area available to harvest wind energy.
		Coastal area	Next to the generation potential on land, the offshore generation potential is also relevant for wind energy systems.
Generation	Site location	-	Site location has been left out since the outcomes are assumed to be closely related to the central/decentral nature.
	Technology used		
	Central/Decentral nature		
	Material requirements	Critical materials needed	Since material requirements includes a lot of different materials, which are not all assumed to be important, the indicator has been specified to critical materials needed. It is assumed that critical materials will mostly impact interstate relations. This indicator merely focuses on raw materials, not on products or components made from these materials.
Distribution	Network technology and topology		
	Operating systems		
	Storage means		
		Neighbouring countries	The geographic context in which the system is embedded is assumed to be an important geographic characteristic of the system that influences potential energy relations.
		Vulnerabilities in system	Vulnerabilities in a system affect the way in which the system can be attacked, and therewith also the potential conflicts between countries.
Business models	Decentral business model	-	Since the main focus of this study is to examine the arising energy trade relations **between** countries, business models within countries are not taken into account.
	Flexibility trading	-	Idem
Electricity market structure	Product characteristics	-	Product characteristics outline technical aspects of the product which might influence the market. Most of the aspects have been captured in other variables already. For example, the abundant character of wind makes it accessible for almost everyone, so barriers to entry the market are low. This is therefore captured under barriers to entry/exit. Or, the electric nature of electricity has impact on the market scope, this is captured under market scope.
	Time constraints	-	Refers to time constraints of generation. Significant time constraints in generation might lead to storage. Hence, we feel that this indicator partly overlaps with intermittency and storage means and is therefore not included.
	Market scope		
	Number of producers and consumers		
	Barriers to entry/exist		
	Price stability		
	Nature of good	-	The nature of the good refers to how whether a good can be distinguished from competing products from other suppliers. Electricity is often considered as non-distinguishable. In this study, one could argue that green electricity can substitute grey electricity but since both forms are often mixed in the case we are examining,

			this is difficult to assess. Besides, this variable is partly captured by number of producers and consumers since this also outlines whether there are asymmetric dependencies.
Trade patterns	Trade flows	Trade flows of materials/products	Trade flows is very general. This indictor focusses on the trade flows that arise due to energy technologies used.
	Import/export ratio	Trade flows of energy sources/carriers	These trade flows focus on trade of energy sources and carriers. The import/export ratio of these flows are outlined in the energy security section, the aim of this part is merely to map the new trade flows and the respective countries.
	Interconnectivity between countries		
	Trade creation and diversion	-	This variable aims to outline the shifting trade relations with new or different partners. Since we already look into trade flows and interconnectivity, we leave this variable out.
Welfare implications	GDP growth	-	Since the main focus of this study is to examine the arising energy trade relations **between** countries, welfare implications within countries are not taken into account.
	Allocative efficiency	-	Idem
	Distribution of costs and benefits	-	Idem