Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Energy

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Impact of Enhanced Spatial Resolution in Energy System Modeling: Investigating the Impact of Bidding Zone Disaggregation and Cost-Effective Grid Expansion in the North Sea

Master's thesis in Energy and Environmental Engineering
Supervisor: Hossein Farahmand
Co-supervisor: Dana Reulein, Shweta Tiwari, and Christian Andresen
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Summary

Urgent actions are needed in order to combat the effects of climate change. Transforming the fossil-based energy system over to a renewable energy source-based system is integral to lowering emissions. The European Union has set a target for their member countries to reduce greenhouse gas emissions by 55% compared to 1990 levels by the year 2030 [1]. To achieve this they need a lot of new and renewable energy sources, like the planned 60 GW offshore wind power in the North Sea. Norway on their part aims to allocate areas with a combined offshore wind capacity of 30 GW by 2040 [2].

Energy system models can be utilized in order to explore the outcomes of low-carbon energy system scenarios. In this thesis, five different scenarios were created for the open-source energy system model, GENeSYS-MOD. These were all based on the gradual development openENTRANCE scenario. A base case, Denmark disaggregated, offshore node connected to NO2, offshore node connected to NO2 and DK1, offshore node connected to NO2, DK1, and UK. These scenarios were studied in order to answer the following research questions:

Research question 1: To investigate whether the disaggregation of Denmark into bidding zones has a meaningful impact on the energy system or if it is negligible.

Research question 2: What is the cost-effective grid expansion strategy from the Norwegian offshore wind area to the neighboring countries around the North Sea?

Results regarding research question 1 highlighted the significance of disaggregation, as it uncovered a bottleneck in the Danish energy system, resulting in a 21.9% difference in installed capacities in Denmark between the two scenarios. The disaggregated scenario had the least total capacity of 63.2 GW in 2050.

Results regarding research question 2 showed a clear trend that favored a meshed grid structure in the North Sea. The grid expansion, which connected to NO2, DK1, and UK, resulted in the most cost-effective solution and produced the most significant capacity expansion of offshore wind in the North Sea.

Sammendrag

Rask handling er nødvendig for å bekjempe effektene av klimaendingene. Å omstille det fossilbaserte energisystemet til et fornybart energibasert system, er avgjørende for å senke utslipp. Den europeiske unionen har satt et mål for medlemslandene sine om å redusere klimagassutslippene med 55% sammenlignet med nivåene fra 1990 innen 2030[1]. For å oppnå dette trenger de mange nye og fornybare energikilder, slik som 60 GW planlagt offshore vindkraft i Nordsjøen. Norge på sin side har som mål å tildele områder med en samlet kapasitet på 30 GW offshore vindkraft innen 2040[2].

Energisystem modellering kan bli benyttet for å utforske utfall av lav-utslipp energi system scenarioer. I denne masteroppgaven ble det opprettet fem ulike scenarier for energisystemmodellen GENeSYS-MOD. Disse er basert på gradual development openENTRANCE-scenariet: en base case, Danmark disaggregert, offshore-sone til NO2, offshore-sone koblet til NO2 og DK1, offshore-sone koblet til NO2, DK1 og UK. Disse scenariene ble utforsket for å besvare de følgende forskningsspørsmålene:

Forskningsspørsmål 1: Om å disaggregere Danmark har en signifikant betydning på energisystemet eller om det er neglisjerbart?

Forskningsspørsmål 2: Hva er den mest kostnadseffektive strategien for nettutvidelse fra det norske offshore vindområdet til nabolandene rundt Nordsjøen?

Resultatene angående forskningsspørsmål 1 understreket betydningen av oppdeling, da det avdekket en flaskehals i det danske energisystemet som resulterte i en 25% forskjell i installert kapasitet mellom de to scenarioene. Den oppdelte scenarien hadde den laveste totale kapasiteten.

Resultatene angående forskningsspørsmål 2 viste en tydelig trend som favoriserte en sammenkoblet struktur for strømnett i Nordsjøen. Strategien for nettutvidelse, som involverte tilkobling til NO2, DK1 og UK, resulterte i den mest kostnadseffektive løsningen og førte til den mest betydelige kapasitetsutvidelsen av offshore vind i Nordsjøen.

Preface

This Master's Thesis marks the completion of our Master of Science (MSc) degrees in Energy and Environmental Engineering at the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU). It was written from January to June 2023 under the guidance and supervision of Professor Hossein Farahmand with the Department of Electric Energy (IEL) at NTNU, and co-supervised by Dana Reulein at IEL, SINTEF researcher Shweta Tiwari and SINTEF researcher Christian Andresen. The project has been a collaboration between IEL and SINTEF. This thesis is part of the Ocean Grid research, Energy market design, project, which is led by SINTEF Energy and is part of a larger national research project called Ocean Grid[3]. This thesis has contributed to the publication of a conference paper that has been approved but is yet to be published. It was presented at the IEEE International Symposium on Industrial Electronics (ISIE) in Helsinki, Finland in June 2023 by Dana Reulein.

This thesis builds upon our previous specialization project, titled ”Offshore price area modeling,” which was concluded in December 2022. The specialization project served as a basis for this thesis, as it involved the development of the openENTRANCE dataset and its adaptation to the 3.1 version of GENeSYS-MOD. Certain sections from the specialization project, specifically chapters 1, 2, 3, 4, and 5, have been incorporated into the master thesis and expanded where necessary.

We would like to use this preface to thank our highly skilled associates. Our lead supervisor has been Hossein Farahmand. His engagement, effort, and curiosity in our work have been hugely motivating. Even in periods of slow progress due to issues with modeling, his positive attitude led to a great work environment. In forming the thesis framework, Farahmand set up a collaboration that allowed us to work as a team alongside top-level researchers. This was initially outside of our comfort zone, but we have grown from the experience. We consider ourselves privileged and fortunate to have had the opportunity to collaborate with such compassionate and talented individuals.

Shweta Tiwari and Dana Raulein deserve significant credit for their contributions to this thesis. Their valuable input, problem-solving skills, and expertise in various fields have greatly enriched our work throughout the semester. We deeply appreciate their collaboration and the positive impact they have had on this thesis.

Even though she was not a part of our work on the master thesis, we would like to thank Sarah Schmidt for her help with our specialization project when she worked for SINTEF Energy. She gave us invaluable insight into the GENeSYS-MOD model and generously shared her experiences and knowledge in academic writing.

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Abbreviations

ACER = Agency Cooperation Energy Regulators
BEV = Battery Electrical Vehicle
CCS = Carbon Capture and Storage
CO2(-equ) = Carbon dioxide equivalents
DAC = Direct Air Capture
EFTA = European Free Trade Association
ETS = Emission Trading System
EU = European Union
EVs = Electric Vehicles
FOWT = Floating Offshore Wind Turbine
GAMS = General Algebraic Modelling System
GD = Gradual Development
GHG = Greenhouse gases
GW = Giga Watt
HLI = Heat Low Industrial
HLR = Heat Low Residential
HMI = Heat Medium Industrial
HVDC = High Voltage Direct Current
IEA = International Energy Agency
IFE = Institute for Energy Technology
NSEC = North Sea Energy Cooperation
NTC = Net Transfer Capacities
NNSzero scenario = Nordics and North Sea zero emission scenario
NVE = Norwegian Water Resources and Energy Directorate
OCGT = Open Cycle Gas Turbine
openENTRANCE = open ENergy TRansition ANalyses for a low-Carbon Economy
OSeMOSYS = Open-Source Energy Modeling System
PHS = Pumped Hydro Storage
PtX = Power-to-X
PV = Photovoltaic
RES = Renewable Energy Source
SSB = Norwegian Bureau of Statistics
TU Berlin = Technical University of Berlin
WEO = World energy outlook

Chapter 1

Introduction

Reducing the effects of climate change is considered one of the biggest challenges humankind has ever faced. There needs to be a substantial reduction in the emissions of greenhouse gasses (GHG) and in particular the emissions of carbon dioxide (CO_2). CO_2 is estimated to contribute to approximately two-thirds of the total warming caused by greenhouse gas emissions[13]. To limit the negative consequences of global warming, 196 countries gathered at the 2015 United Nations Climate Change Conference COP 21 in Paris to create a legally binding treaty with the goal to cap temperature increase at 2°C, preferably closer to 1.5°C [14]. Partly as a result of this agreement, the European Union has created its own 2030 Climate Target Plan. This aims to reduce the emissions of GHG by at least 55%, compared to 1990 emission levels by 2030 and to be climate neutral by 2050 [1]. Most of the GHG emissions come from the energy sector in 2020 [15]. Hence, decarbonization of the energy sector will play an important role in reaching the targets of the Paris Agreement and the 2030 Climate Target Plan.

Predicting and understanding the future development of something as large and complex as the energy system is challenging. There are substantial uncertainties regarding future politics as well as societal and technological developments. That is why many big actors like the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), the European Union (EU), and large international and national research projects are developing different pathways to understand how we can archive a greener and more sustainable future. Many different pathways need to be explored in order to find politically viable, cost-efficient, and socially fair decarbonization strategies. Often, these pathways look at how differences in policies, societal and technological development impact cost, and GHG emission developments.

For decades, hydropower has served as the foundational source of energy in Norway, providing a reliable backbone to the country's power supply. However, growing concerns surrounding the environmental consequences of large-scale hydropower projects, coupled with the challenges of expanding such initiatives, have underscored the necessity for Norway to diversify its energy portfolio. In this context, offshore wind power presents a compelling opportunity to achieve this diversification by harnessing the wind resources available in the North Sea and the Norwegian Sea. The long coastline and good offshore wind conditions create an ideal environment for harnessing offshore wind energy. This attribute bears significant potential in driving the decarbonization efforts of the Norwegian energy system [2]. However, the expansion of offshore wind and offshore grid infrastructure presents numerous challenges that need to be addressed.

Ocean Grid is a large national research project, funded by the Norwegian government and the partners involved. It aims at developing new technologies and solutions for offshore wind in Norway and thereby help to reach climate goals. The seventeen world-class partners of the Ocean Grid project consist of eight energy companies and developers, six suppliers and manufacturers, and three research and innovation organizations that/who work together to lay the groundwork for future green job creation and profitable development of offshore wind in Norway [3]. The Ocean Grid project is divided into five sub-projects: Offshore grid development, Wet design cables, Subsea substation, Floating High voltage direct current (HVDC) platform, and Ocean grid research. This project is part of the Ocean grid research, Energy market design, which is led by SINTEF Energy. It investigates the impact of energy market design regarding offshore wind when integrated into the European power market, and how this will affect the potential price variations and offshore wind farm profitability in general.

1.1 Objective and Scope

This thesis utilizes the GENeSYS-MOD energy system model to analyze the integration of offshore wind development into the countries surrounding the North Sea. In GENeSYS-MOD, integrating offshore wind development into existing regions poses challenges due to the offshore location and higher transmission costs [16]. This leads to inaccuracies in setting capital costs for offshore wind technologies. To address this issue, GENeSYS-MOD is expanded to include standalone nodes representing large-scale offshore wind farm areas. This enables extensive sensitivity analysis of offshore wind grid infrastructure and evaluation of capacity expansion, transmission capacity, power production, import/export, emissions, and the marginal cost of power for connected regions. The analysis focuses on the electricity sector and transmission capacities, including the electrification of the transport, heating, and industry sectors as exogenous parameters in the model. The thesis involves creating a Nordic and North Sea-focused dataset based on the Open ENTRANCE gradual development dataset [4], with the increased geographic resolution of Denmark. This is done in collaboration with SINTEF as part of the Ocean Grid project. The modeling framework details the energy sector, including domestic transport and prominent industries. This finer geographical resolution in Denmark allows for a more accurate depiction of grid bottlenecks and enhances the system description in Denmark. The time period modeled spans from 2018 to 2050, with data specified from 2018 and results generated for subsequent time steps (2025, 2030, 2035, 2040, 2045, 2050) as optimal system descriptions obtained through the extended GENeSYS-MOD. Within this thesis, the following two research questions are attempted to be answered:

- Research question 1: Investigate whether the disaggregation of Denmark into bidding zones has a meaningful impact on the energy system or if it is negligible.

- Research question 2: What is the cost-effective grid expansion strategy from the Norwegian offshore wind area to the neighboring countries around the North Sea?

1.2 Contribution

This thesis makes a dual contribution, consisting of two parts that collectively enhance the representation of the Norwegian energy system within GENeSYS-MOD. Firstly, this thesis introduces the incorporation of an offshore node into the openENTRANCE dataset for GENeSYS-MOD. Including an individual offshore price area offers valuable insights into identifying optimal market designs that foster profitability for offshore wind farm developers and operators. Multiple scenarios are tested, varying the transmission connections to the offshore node, providing guidance to policymakers and industries in making informed decisions for future grid development. Secondly. the thesis contributes to enhancing the accuracy of the Danish energy system. The division into bidding zones allows for identifying limitations or issues within the power grid that would otherwise remain undetected. A comprehensive depiction of Denmark is crucial for accurately representing Norwegian power trade to the continental energy system. Although Swedish disaggregation is not currently implemented in this thesis, all relevant data is archived for future implementation and further research.

1.3 Thesis structure

Background Chapter 2 is a literature study divided into three parts. The first part presents recent policy developments for the world, Europe, and Norway. It showcases how we have come to today's pleading policy frameworks and explores the way forward. The second part gives an overview of the developments in energy system modeling. It briefly describes the most established models currently in use, how they work, and what energy system modeling contribute to help plan the future expansion of the power grid. The third section gives a brief introduction to capital investment costs related to offshore transmission grids.

Modeling energy systems Chapter 3 presents a more detailed overview of the major energy system modeling frameworks TIMES, PRIMES, and GENeSYS-MOD and the actors who use them.

Decarbonization scenarios Chapter 4 provides an overview of important decarbonization scenarios explored through energy system modeling frameworks by the EU, IEA, NVE, and Statkraft. This includes the openENTRANCE Gradual development scenario used in this thesis.

Development of the Nordics and North Sea zero emission scenario Chapter 5 describes the work conducted throughout this thesis. This includes the development of the dataset, the implementation of an offshore price area, the disaggregation of Denmark, and a brief section on how this thesis contributed to the publication of a conference paper. It also mentions some problems and inaccuracies with the current model.

Results and Discussion Chapter 6 of this thesis presents the findings from five distinct scenarios. These scenarios include the base case, a version with Denmark disaggregated, as well as the addition of an offshore node connected to NO2, NO2 and DK1, and lastly NO2, DK1, and UK. Results like capacity expansion, emissions, power trade, transmission capacity, and marginal costs are presented. The results are critically analyzed and discussed. Findings connected to the research questions are highlighted and explained.

Conclusion Chapter 7 answers the two research questions of the thesis, lists assumptions and limitations in the model, and finally provides points for future work.

Chapter 2

Background

2.1 Recent policy developments

The world is currently facing a global energy crisis. After Russia's invasion of Ukraine in early 2022, the EU and most of the Western world chose to penalize Russia by applying restrictions to trade in most sectors, including energy. This new geopolitical situation exposed just how dependent the European energy system is on one external economy. At the same time, Europe's large dependencies on predominately imported fossil fuels became clear. This has turned into an energy security challenge, quickly rising in importance. Events like the sabotage of the Nord Stream pipelines in September of 2022 and sanctions on Russia's trade imposed by the West have led to a massive energy shortage. This resulted in drastically increasing energy and electricity prices to levels never seen before [17]. In an attempt to counter this, not only has the discussion on nuclear power gained new momentum, but already decommissioned coal power plants have been put back onto the grid and the use of coal has started to increase, generating more GHG emissions through the burning of coal to produce electricity. This is a step in the wrong direction and only contributes to more global warming. The transition to a renewable-based and sustainable energy system has never been more important.

With the EU Reference scenario, the EU investigates how different plans and policies affect the cost and emissions of GHG for the European member countries.

One of the plans examined in the EU Reference Scenario is the European Green Deal. It is the EUs plan for how to become the first climate-neutral continent by 2050. It includes strategies for sustainability in many areas including energy, forestry, industry, circular economy, and biodiversity. The energy sector alone is responsible for 75% of the EU's carbon footprint [18]. Previously, all countries in the EU were supposed to reduce their GHG emissions by 40% in 2030 compared to 1990 levels according to the Paris Agreement [14]. The EU has increased its ambition to counter climate change, and in July 2021, they submitted the Fit for 55 package. It is legislation that binds EU member countries to reduce their GHG emissions by at least 55% compared to 1990 levels. The end goal is the same, climate neutrality by 2050, but the transition away from fossil fuels is envisioned to happen faster in the Fit for 55 plan [19].

The Fit for 55 plan aims at exploiting large amounts of renewable resources; in addition to solar and hydro, the plan opts for major developments of offshore wind. In November 2020, the EU laid out a strategy regarding offshore wind expansion. In 2020 12 GW was installed, which is envisioned to increase to 60 GW by 2030 and 300 GW by 2050 [20]. This large development of offshore wind and other renewable resources is not only a measure to reduce the EU's GHG emissions from the energy sector but also an attempt to increase economic output. This planned offshore wind capacity is part of the NextGenerationEU program, which aims at getting Europe back on its feet after the pandemic, investing over 800 billion Euro in different sectors to stimulate the economy, one of these being the energy sector [21].

The EU has five different sea basins which could harness offshore wind power production: the Baltic Sea, the North Sea, the Mediterranean Sea, the Black Sea, and the Eastern Atlantic [22]. The North Sea is especially beneficial for offshore wind since it can act as a junction point for the central European and the Nordic power grid, encouraging international power trade and at the same time providing green energy to the EU and the Nordics[23]. The North Sea Energy Cooperation (NSEC) consists of countries bordering the North Sea: Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway, Sweden, and the EU. The UK left NSEC in 2020 when they decided to leave the EU. The countries that are a part of NSEC will cooperate and plan out the development of the North Sea every three years. The nine-member countries reached a joint statement where want to install 260 GW of offshore wind power by 2050, 85% of the EU's goal of 300 GW. The NSEC has a higher goal for 2030 than the EU, aiming for 76 GW offshore wind power instead of 60 GW [23].

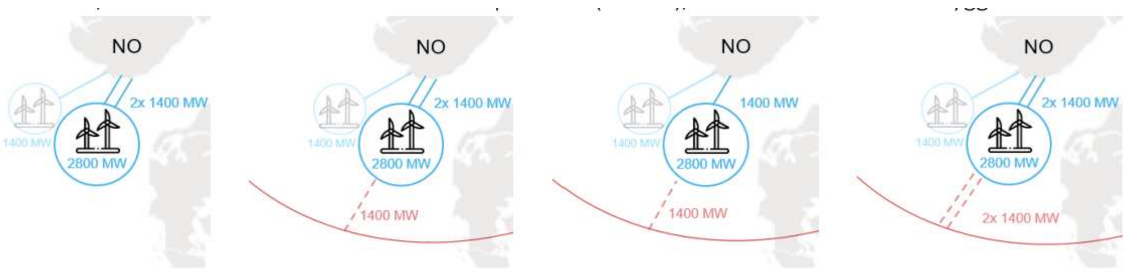
In general, one of the main and fundamental challenges with offshore wind and variable renewable power is its intermittency. Wind power only produces electricity when the wind blows, and without sufficient storage capacities, the production volumes cannot be matched with the demand patterns. Norway has a unique possibility to smooth out offshore wind power variations by balancing it with its large hydropower system. Pumped hydropower is used to pump water into an upper reservoir when the power is cheap and available, as well as managing large production units connected to a reservoir to balance variable wind power production. As such, the hydropower system as a whole can function as a large battery. Nicola Destro, Magnus Korpås, and Julian F. Sauterleute(2016) "Smoothing of Offshore Wind Power Variations with Norwegian Pumped Hydro: Case Study" looks at a case where offshore capacity in the North Sea reaches 94.6 GW capacity in 2030. This is much higher than the current goal the EU has at 60 GW. Even though they use a high offshore wind maximum capacity in their model, Norwegian hydropower could cover 70% of the balancing request for offshore wind power in the North Sea [24].

The Norwegian government has the ambition to assign areas that can produce 30 GW offshore wind power within 2040 [2]. Norway has great premises for offshore wind. It has a long coastline combined with a strong industry related to offshore shipping and offshore oil which can be redirected towards renewable industries. The Norwegian government believes Norway can become a world-leading developer of offshore wind technology, especially floating offshore wind turbines (FOWT) [25]. A large concern for offshore wind power development along the Norwegian coastline is its profitability [26]. The varying depths, combined with a complex seabed to anchor, make the cost per MW installed power higher than for the rest of Europe. NVE compared the prices of offshore wind in Sørlige Nordsjø II and Sanskallen Sørøya nord, which have similar conditions as Utsira Nord, to the average MW price of offshore wind power in Europe. Wind parks that require floating foundations, like Sanskallen Sørøya Nord and Utsira Nord, have a very high cost per MW because of the new and immature technology used for FOWT, see Figure 2.1.

Figure 2.1: Comparison between Norwegian offshore wind prices and the rest of Europe by the Norwegian water resource and energy directorate(NVE) [9].

The most recent plans for offshore wind in Norway involve Utsira Nord and Sørlige Nordsjø II. These areas require new technology to support FOWT because of their great depths and complicated seabed. The plan is to auction the areas to contractors that meet a set of requirements determined by the state. The contractors for both areas will be decided in 2023. Utsira Nord will be divided into three parts of up to 500MW each, giving a total effect of 1500MW installed power [27]. Sørlige Nordsjø II has double this potential, namely 3000MW. Because of the technical challenges, especially regarding Utsira Nord, which has an average depth of 267 m [10]. The leader for the Norwegian Oil and Energy department, Terje Aasland, said in a press conference (06/12/2022) that they envision the offshore wind power plants to be operational around 2029-2030 [25].

There has been a lot of debate regarding the structure of the power grid connecting the offshore wind farm in Sørlige Nordsø II. There are two main solutions. For the radial approach, all the electricity goes back to Norway, where it is used



2800 MW radial **2800 MW asymmetrisk hybrid** **2800 MW liten hybrid** **2800 MW stor hybrid**

Figure 2.2: Different power grid solutions for Sørlige Nordsjø II [10].

or traded. Or the Hybrid approach, where the offshore wind farm acts as an interconnection between Norway and neighboring countries. Different grid solutions are visualized in figure 2.2. Statnett did a report on the profitability of the different solutions[10] [26]. They concluded that the Hybrid approach would create the biggest system surplus. Trade with the United Kingdom would be especially profitable for Norway between 2030-2040. After 2040 they estimated that the electricity prices in Europe would start to even out, making trade less beneficial [10]. Even so, the Norwegian government chose to declare 3000 MW capacity with the radial approach [25]. This decision could be an attempt to calm down the general public in Norway who have shown dissatisfaction with the high electricity prices while Norway at the same time set all-time records for power export [28].

An offshore wind park very similar to Utsira Nord, Trollvind, has recently been put on hold due to lacking profitability. It would have consisted of floating offshore with a depth ranging from 250-400 m. The total capacity was planned to be around 1 GW. Geographically it is very close to the Utsira Nord project [29]. Equinor, who is the leading developer for Trollvind, blames the general price increase and inflation when deeming the project unprofitable [30]. This unusually high price increase, caused by the pandemic and Ukrainian war[31], is also reflected in new cost estimations for Sørlige Nordsjø II. The Norwegian government planned 15 billion NOK in subsidies, but this has now been increased to 23 billion [32]. There is now rising uncertainty about whether offshore wind is an economic opportunity or a financial drain [33][34].

2.2 Literature study - Energy system modeling development

Global political targets are complex and difficult to reach. Reaching the 1,5 °C goal is one of these global political targets. Success here relies heavily on the transition to a renewable and more sustainable energy system [17]. How to best achieve this has no definite answer. Insights generated by energy system models can help guide decision-makers to take fact-based and well-informed decisions to drive the transition to a more sustainable energy system [35]. Energy system models provide a cost-optimal solution to meet future demands. By putting different restraints into the models, one can test the effects of new policies and investment plans on optimal system development over time. Since the early 1980s, energy models have been used to develop beneficial energy policies and strategies [36]. Over the past two decades, there has been a substantial rise in the deployment of variable renewable power sources, coinciding with the gradual reduction of nuclear power following the Fukushima disaster in 2011. Balancing this change is complicated, and the importance of energy system models has continued to grow[35]. Energy systems have become incredibly complex and computationally heavy depending on the temporal and spatial resolutions, represented sectors, and energy carriers. That is why several models have been developed to cover and analyze different aspects of the energy system [36].

There are two main ways to model an energy system. The top-down approach and the bottom-up approach. They both have their strengths and weaknesses. Users of the energy models, like policymakers, are often not sufficiently aware of the large difference in how results need to be interpreted based on the type of modeling approach used. A bottom-up energy system model incorporates a lot of technological detail. This method is mostly used by engineers, natural scientists, and energy supply companies [35]. The drawbacks of bottom-up energy system models are their large requirement of data and future technological assumptions like operation costs, investment costs, and technology diffusion [37]. These models also tend to neglect the costs of macro effects related to technological change on overall economic activity, employment, and prices [38].

The top-down model shines where the bottom-up model struggles. It captures feedback effects related to welfare, employment, and economic growth. This gives a more comprehensive and consistent picture of the economic impacts the energy system has on a region or a country [35]. The lack of technological detail as input makes the model give a rather generalized output. This is one of the drawbacks of the top-down approach that is important to keep in mind especially when working with models with a long temporal resolution where technological development is substantial [38].

Combining the two modeling types would greatly strengthen the insights energy system modeling can generate. The MARKAL model implements macroeconomic and microeconomic features like the ability to adapt to price changes and trade of emission permits [39]. It was developed by the International Energy Agency (IEA) to help policymakers. The current TIMES model is an extension of the MARKAL model. It adds flexible time periods, commodity-related variables, climate equations, and more [40]. The problem with implementing the top-down features to a bottom-up approach is the increase in complexity of the model. Large amounts of technical data with implicit bounds turn unavoidably very complex very fast when integrated with explicit price variations to account for income effects [38]. Computing power has increased greatly in the last decades since the first energy system models were developed, but at the same pace, the problem descriptions have increased in complexity. Hence, the complexity still reaches levels where normal computing is the bottleneck to more detail [41].

The first energy system models focused on societal and economic analysis [35]. Now the models need to achieve societal, economic, environmental, and technological analysis. The recent integration of large-scale variable renewable power generation into the energy system demands more flexibility than previous models have accounted for [42]. Flexibility problems can occur when there is a forecast error in power demand or production. Models with medium to long temporal resolutions often reduce the number of time slices to reduce the computing work, which leads to lower accuracy to assess short-term flexibility needs [36].

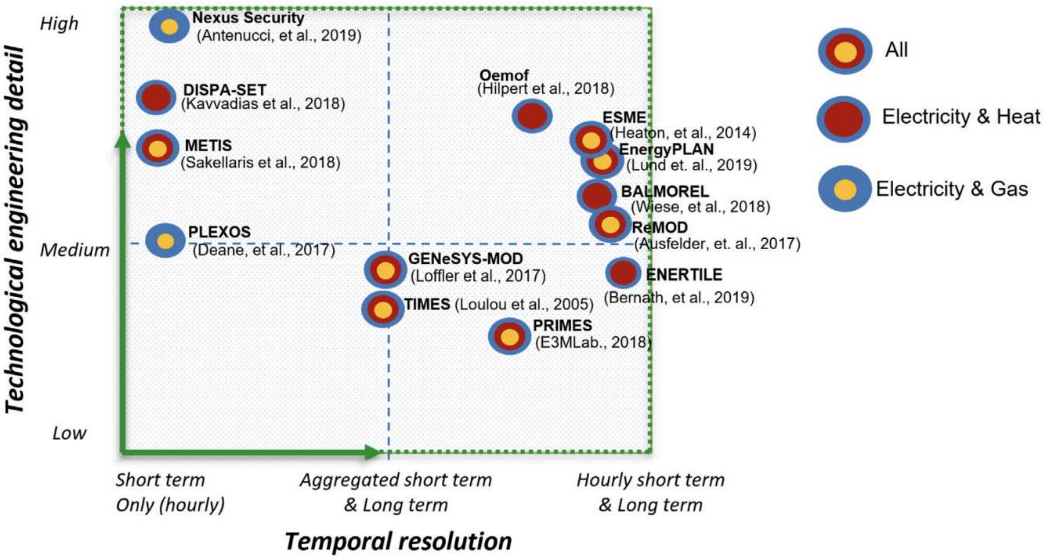


Figure 2.3: Technological detail and temporal resolution of multi-energy carrier models [11].

When looking at energy system models, it is natural to look at what scope they cover. Like what technologies the model includes, how detailed the technological data is, and what spatial and temporal resolution it permits. Figure 2.3 shows the scope for some of the most common energy system models. PRIMES, TIMES, EMPIRE [43] and GENeSYS-MOD lie closely together since they have a lot of similarities in what sectors they cover, temporal resolution, and technological detail [11]. One significant reason for utilizing GENeSYS-MOD in this thesis is that it is the only open-source energy system model among the discussed models above.

A major focus point of current research is the interaction between energy carriers. Here new insights and needs for better implementations call for more research and further development. Especially the interconnection between electricity and hydrogen offers a lot of potential for new solutions. Demand side management in multi-carrier systems and the inclusion of prosumers to create local flexibility in the market are just starting to get explored [11]. This is predicted to become a substantial part of the energy system in the future and needs to be integrated into the energy system models.

Adding new parameters into models adds uncertainty. Models only investigate a limited set of different parameters at a time. There is no model that can investigate how all the parameters interconnect and affect each other, creating a large cumulative uncertainty. Models also largely ignore the possibility of biased and faulty policies creating stochasticity in the long term [11].

Today's energy system models also fail to adequately represent the characteristics of developing countries. In order to make electricity available for all within 2030, better energy system models for developing countries are essential. The lack of focus to capture informal sectors and non-monetary transactions make current models less suitable for policy decisions in these countries [44].

2.3 Literature study - Capital Investment Costs

In the GENeSYS-MOD energy system model, one of the underlying assumptions is that the investment costs of offshore wind are determined by the distance from shore. This implies that as offshore wind capacity and the use of deeper offshore wind technologies increase, the associated investment costs also rise. This is because the cost of transmission capacity, submarine HVDC cables, is included in the technology costs. With the development of the model to include offshore wind farms as standalone regions the methodology of this becomes mute. As the cost of transmission capacity expansion is doubled from the inter-nodal connections and the technology capital cost. For future work, the prices and cost methodology for the offshore wind in the offshore nodes should be updated. This is imperative to achieve higher accuracy in the model. There are several reasons why the investment costs of offshore wind are important to be realistic. The investment cost directly influences the viability and attractiveness of offshore wind projects, determining their feasibility. They also directly impact the affordability of offshore wind energy, making it a competitive alternative to conventional energy sources. A reduction in investment costs will also lead to lower costs in the future as when more projects are developed, the industry scales up, and advancements in turbine technology contribute to cost reductions. This is the motivation for acquiring and gathering information for future developments in GENeSYS-MOD offshore capital cost values and methodology through a literature study.[45]

During the literature study into capital investment costs for offshore-wind, it was found that approximately 70%–75% of the total cost of offshore wind power production is related to initial capital investment costs. According to Arshad and O'Kelly's [46], the initial investment costs of offshore wind can be divided into different categories, with approximate percentages allocated to each category as a proportion of the total capital investment costs. 8% - 30% can be expected to be allocated to development and engineering costs, licensing procedures, consultancy, permits, supervision, control and data acquisition, and monitoring systems. 30% - 50% is the wind turbine cost, which includes production, transportation, and installation. Construction costs are 15% – 25%, which includes foundation, transportation, and installation of tower and turbine and other infrastructure (e.g. access roads for onshore) necessary for turbine installation. The last post is the costs of the grid connections, including cabling, substations, and buildings, This makes up the remaining 15% - 30%. In this paper, the percentage made of the initial investment costs of offshore wind energy is based on a comparison between offshore wind projects. The paper also provides an estimated reduction in investment costs for deep offshore wind in 2020, 2030, and 2050. 25% 36% AND 50% respectively. [46]

Chapter 3

Energy system modeling frameworks

Energy system modeling involves the creation of computer models to analyze energy systems. Various established models, run by national governments, organizations, and researchers, exist for this purpose. Some models are proprietary and have been developed over an extended period, but they have faced criticism for lacking transparency. This has led to the development of new open-source models. In the context of analyzing the European energy transition towards sustainability, prominent modeling frameworks include PRIMES, TIMES, and OSeMOSYS. For our study, we have utilized the GENeSYS-MOD model, which is based on OSeMOSYS. This section provides a brief overview of PRIMES and TIMES, followed by a description of our chosen modeling framework, GENeSYS-MOD.

3.1 PRIMES

PRIMES (Price-induced market equilibrium system) is a bottom-up energy system model and a partial equilibrium model. It is used as the energy system model in the EU Reference Scenario published by the European Commission. It spans from medium to long term, up to 70 years, with 5-year intervals. The model includes the EU Member States and EFTA(European Free Trade Association) countries. The PRIMES model offers comprehensive analyses of energy system CO2 emissions and economic impacts, both at the EU level and on a country-specific basis. The model focuses on utility maximization and cost minimization, influenced by market equilibrium. PRIMES is capable of handling market distortions, barriers to rational decisions, behavior, and market coordination issues. The model formulates the decisions made by agents based on microeconomic principles such as utility maximization and can explicitly determine prices. It is bound by constraints like transfer capacity, technologies, and energy demand. It can be combined with other models like GLOBIOM and GAINS to gain representative results for multiple sectors [47].

3.2 TIMES

TIMES (The Integrated MARKAL-EFOM System) model generator is a widely used energy system modeling framework developed by the IEA-ETSAP (Energy Technology Systems Analysis Program). In Norway, it is utilized by the regulator NVE to provide annual long-term power market reports and by the Institute for Energy Technology (IFE). TIMES is typically used for energy and environment analysis. The model generator uses a combination of two systematic approaches for modeling; part engineering and part economic. The purpose is to optimize the cost of the energy system, in a medium to long-term time frame, based on constraints set by the user's demand [48].

The supply side encompasses fuel mining, primary and secondary production, and exogenous imports and exports. The consumers are structured into five sectors, residential, commercial, transport, agricultural and industrial. TIMES optimizes across all sectors and time periods. The model presumes perfect foresight, meaning, all decisions on investments are made with full knowledge of the future. The result is the optimal mix of technologies and fuels to meet a specific demand while keeping emissions under the constraints provided. The market reaches equilibrium when the demand and supply coincide on a production quantity, the price at this point is the market clearing (MC) price. The model outputs comprise system cost, energy flows, GHG emissions, capacities for technologies, energy costs, energy commodity prices, and marginal emissions abatement costs [48].

3.3 GENeSYS-MOD

The Global Energy System Model (GENeSYS-MOD) is an open-source, linear optimization model that minimizes total system costs. It was developed by Löffler et al. at Technical University Berlin and first published in 2017 [12]. It is written in General Algebraic Modeling Language (GAMS), which is a high-level modeling system for mathematical programming and optimization and requires a license. It is based on the modeling framework OSeMOSYS. The model has been extended significantly from OSeMOSYS by the TU Berlin team [12]. Model inputs are demand levels and development, time series for renewable production and demand, technology descriptions and cost developments, and carbon costs/limits or budget. The model computes the optimal capacity expansion, including trade, and carbon costs or emission levels. GENeSYS-MOD covers the power, heating, and transport sector and a variety of sectors integrating energy carriers.

Model Description:
The objective function in GENeSYS-MOD minimizes the net cost of an energy system over time while meeting the demands given by the user. The objective function is defined by:

$$min\ cost = \sum_{r}\sum_{t}\sum_{y} TDC_{r,t,y} + \sum_{r}\sum_{y} TDTC_{r,y} \tag{3.1}$$

where *TDTC is Total Discounted Trading Cost* and *TDC is Total Discounted Cost* and calculated as:

$$\begin{aligned} TDC_{r,t,y} = DOC_{r,t,y} + DCI_{r,t,y} + DCIS_{r,t,y} \\ + DTEP_{r,t,y} - DSV_{r,t,y} \end{aligned}$$

The abbreviations used in equation 3.3 are: Discounted Operating Cost (DOC), Discounted Capital Investment (DCI), Discounted Capital Investment Storage (DCIS), Discounted Technology Emission Penalty (DTEP), and Discounted Salvage Value (DSV). This equation was gathered from the preprint paper[49] [12]. To achieve this, total system costs are calculated by summing all costs for each technology in each node, time step, and trade. Technology costs include capital investments, operating costs, fixed and variable costs, and emission penalties. The capital costs are determined by a per unit cost for capacity expansion, these are calculated on a per-time step basis, so no new capital cost is added if there is no added capacity in the current year. A technology might be given a salvage value, which is subtracted from the sum of the technology costs when the technology reaches its operational life end or is replaced. All costs are model inputs.

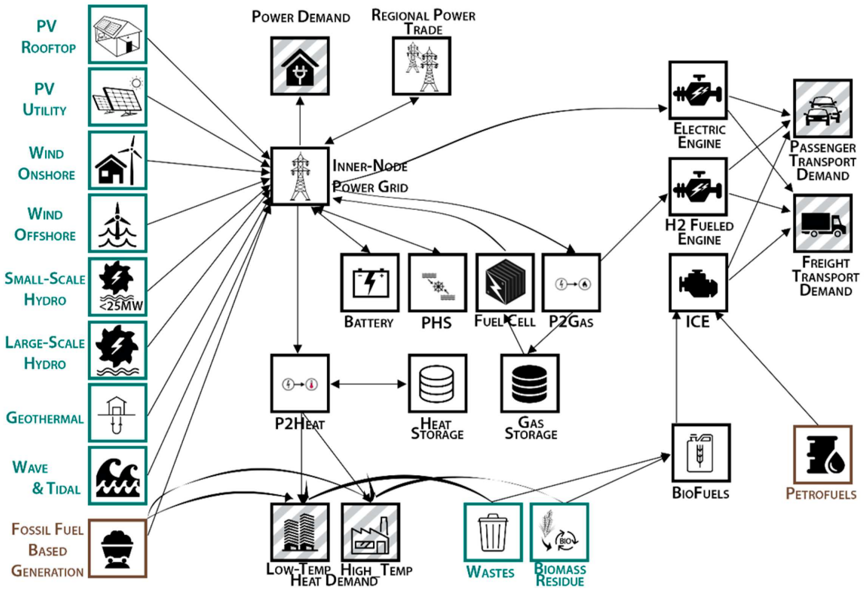


Figure 3.1: Graphical illustration of GENeSYS-MOD with an overview of technologies and their connections [12].

The model can be presented as a flow-based optimization model, where the different nodes are Technologies and are connected by Fuels. The production technologies are posts like wind and solar power. Fuels are the carriers for these Technologies in the form of electricity or fossil fuels [50]. An overview of how GENeSYS-MOD is structured is presented in figure 3.1. It shows the different parameters in GENeSYS-MOD and their connections. The boxes marked with grey stripes are the demands for the model. The brown and blue outlined boxes are the different resources that can be used, where the brown boxes represent fossil fuels while the blue represents renewables. The black outlined boxes are the technologies that make it possible for the resources to be transformed into the ”right” type of energy to be able to meet the different demands. The constraints are set to make natural bounds for the scenarios. This can, e.g., be maximum capacities for certain

Technologies to avoid unrealistic growth and development in short time spans or emissions budgets to limit the maximum allowed emissions for a particular region or time period. And the result of all these constraints is to stay within the limit of 1,5-2 °C increase globally. Below is an overview of how the energy system and hence the optimization problem is described and what terminology is used:

- Technologies: Technologies represent all energy-using, producing, or transforming techniques. So an offshore wind farm with production capacity would be added under technologies as well as a transmission line or a Carbon capture and storage (CCS) unit.
- Sectors: These are the different sectors the technologies are categorized into, like Industry and Buildings.
- Fuels: Fuels differ from technologies in that fuels represent the energy carriers. The carriers are then used to produce, consume or transform energy. Examples of fuels can be H2 and power. Also, demands are handled as ”fuels” and even the area used by PV technologies.
- Year: This is where the temporal resolution of the model is decided. Both the start and end point is decided here, but also the interval for the modeling. This means that if the user sets the start year as 2020 and the end year as 2050 with a 5-year interval, the user will need to provide data for every 5-year leap within the 30 years.
- TimeSlice: This is the traditional way of modeling a year by splitting up how many percent of the hours a year is spent during different representative periods. An example is Q1M and Q1P, this is the time during quarter one of a year that are mornings and peak times, respectively. GENeSYS-MOD offers also an alternative method to represent a year by. Here the user can define how many hours should be used to represent a year and an algorithm tries to mirror the yearly profile by this amount of datapoints [51].
- Mode of: Different technologies have different amounts of different modes. The different modes describe the different inputs/outputs for a technology.

- Region: This is where the spatial resolution of the model is decided. The regions can be whatever the user decides, whether that be continents, countries, spot-price areas, or geographical areas of interest. A region functions as a node. The node contains information on its properties like power production capacity, trade capacities with other nodes (regions), resources, etc.
- Storage: Different types of storage technology need to be defined, and the model can endogenously choose to build the optimal storage capacities. Different types of storage have different lifespans, min and max energy-power ratios, and costs.
- ModalType: modal types are the different types of transportation options available in GENeSYS-MOD.
- Emissions: This is the type of emissions the model takes into account. These can be types of GHGs or just CO2, but also local emissions like for example mercury.

Input data:
The input data for GENeSYS-MOD is formatted as an Excel dataset. The dataset consists of more than fifty sheets of data, located across three different input data files. One file contains all the hourly time series data for renewable production, heat, and demands. The second file contains all technology and scenario-dependent data for each node modeled. The third file contains fallback values for technology data, that can be used when input from the scenario data file is missing. The model can take more input data files if employment effects or detailed demand-response mechanisms are to be studied.

The model takes demand developments as input and finds an optimal solution to meet them. The demand is divided into three sectors: electricity, transport, and heat. The sector is then divided into different categories. Heat is divided into low industry, medium industry, high industry, and low residential. Transport is divided into freight and passenger, then divided further into what type of freight or passenger transport it is, like trucks, planes, boats, and by what technology that transport need is satisfied, that is a diesel or an electric car. The demands are specified for each region for every fifth year. Based on the input data given and restrictions, the model will try to find the lowest overall cost solution, while it satisfies the demands for each region for each time period. The technologies which help meet those demands have restrictions themselves, like cost, development speed, and potential for new capacity additions. Potential capacity could be like how Norway can not have more onshore wind power than its available area for wind farms.

The scenario data file contains a sheet, where the modeling scope is defined through sets. The user decides here how many and what nodes, technologies, and other important parameters to include. The set sheet is followed by sheets describing different resources and energy carriers. A good example of these is the trade sheets, where the user provides info such as the distance between regions, their transmission capacity for gas or power, and the price of trading certain fuels. Other sheets contain residual capacities, which are the capacities left over from periods prior to the modeling period, this is provided on technology and on the node level. The operational lifespan of technologies is provided in another sheet, etc. There are more than 50 datasheets, which means that adding new parameters or nodes is non-trivial, as currently, all necessary data has to be entered manually. However, to remove parameters or nodes, they can just be removed from the sets data sheets and GENeSYS-MOD will omit the removed parameter or node.

Outputs:

Based on the demand developments, technology descriptions, and a set of constraints, GENeSYS-MOD outputs the cost of the optimal solution for the scenario. This cost includes the capacity expansion for the electricity, transport, and heat sector as well as the grid expansion costs needed to meet the demands. It outputs for each time period the capacity, detailed in residual, new, and total, as well as production for each technology for each node. If modeled with a carbon price, the model output the emission amounts per time step, and when modeled with an emission limit or budget, the model provides the shadow price of carbon. [12]

Chapter 4

Decarbonization scenarios

Different actors from research, international organizations, as well as national and European institutions, develop a wide range of pathways and scenarios to better understand how we are to succeed with the enormous endeavor of transitioning to a sustainable energy system. To align the development of our new Nordic and North Sea zero emission dataset with important national and international policy developments, these have been reviewed in the last chapter. To further align with and built on work done by other actors, it is important to understand the assumptions and data used in other influential scenario work.

4.1 World energy outlook by IEA

The World energy outlook (WEO) is published every year by the IEA. The report looks at trends in energy supply and demand, and how these trends affect the economy, energy security, and the environment. The WEO was first published back in 1977 and has been published annually since 1998. It looks at the entire energy system for the whole world. IEA uses the Global Energy and Climate model (GEC), which is a large-scale simulation tool developed by IEA. It includes the entire energy system, from large-scale aggregations to local details. This allows the model to investigate how different technology developments or policies affect the end-user prices in a specific area or country [52].

To use the GEC model, the IEA has developed three scenarios with respective quantitative datasets. Each with different underlying assumptions. The scenarios developed are: Net Zero Emissions by 2050 Scenario (NZE), The Announced Pledges Scenario (APS), and the Stated Policies Scenario (STEPS) [17].

The NZE scenario aims to keep the temperature increase under 1,5°C in 2100. In order to reach this goal, the scenario does not rely on any sectors other than the energy sector. It develops a pathway to reach net zero CO2 emissions for the energy sector by 2050 and universal access to electricity by 2030.

The APS investigates how the current pledges made by countries are on the pathway to net zero emissions in 2050. All recent announcements from countries regarding future plans are updated and implemented in this scenario. Reaching net zero emissions for a region does not mean that the energy sector has reached net zero. If there are other sectors that have negative emissions, like forestry or CCS, the region can still reach net zero even if there are other emissions.

The STEPS is a more conservative version of the APS. It does not take for granted that the goals will be reached, but rather what is really being invested and done, sector by sector in order to achieve them. This separates STEPS from the other scenarios, which have quite clear boundaries and goals. It instead relies on a bottom-up approach with lots of regional data, from pricing policies, specific infrastructure developments, and efficiency standards. It then presents the most cost-effective pathway to approach the goals [53].

4.2 EU reference scenario developed for the European Commission

The EU Reference Scenario is an analysis tool within the energy, transportation, and climate action sector. It helps policymakers create new policy proposals on an analytical basis for the future. In the EU Reference Scenario 2020 specific policy scenarios are used to assess the impact of the different options in the European Green Deal package, which was adopted by the European Commission in July

2021 [54]. The purpose of the EU Reference Scenario is to act as a reference, hence its name. It projects the impact of different trends in technology, fuel prices, macroeconomics, and policies and how this affects the development of the European power system, transport sector, and greenhouse gas emissions. This includes all the 27 member states of the EU as a whole and each country individually. Countries like Norway, Switzerland, and UK are excluded from the model. The scenario also includes the greenhouse gas emissions not related to the energy sector.

The time spans from the year 2020 to 2050. It uses an integrated assessment model, whereas the PRIMES model is used for the energy sector. The scenario aims to have the EU climate-neutral by 2050. Having net zero greenhouse gas emissions and at the same time upholding the Paris Agreement by staying well below the 2°C target. This follows the European Green Deal, which tries to decouple economic growth from resource use. It also accounts for more short-term goals like the EU2030 goals for a renewable energy capacity of 32% within 2030[1]. The sectors that are included in the model are Industry, Residential, Transport, and Tertiary. It also includes hydrogen as an enabling technology. The integrated assessment model has a broader scope than GENeSYS-MOD and also looks at parameters like non-CO2 emissions, LULUCF (Land Use, Land Use Change, Forestry), and air pollution [54].

4.3 NVE’s Long-Term Power Market Analysis

NVE conducts yearly power market analyses for the future [55], and section 4.3 is based on this analysis. The most recent report presents power production, consumption, prices, and trade in Europe, the Nordics, and Norway towards 2040. The spatial resolution of the model is a set of 19 European countries. This list consists of the bigger Western European economies, the Nordics, and the Baltic states. The temporal resolution is 2021 as the base year, and then 2025, 2030, and 2040 for the future. Interpolation is utilized for the progression between the years. NVE used the optimization models TIMES, TheMA, and Samnett [55].

NVE’s rapport was developed in 2021, so it does not take into account the current situation with supply shortage resulting in extra fossil fuel demands from within Europe due to Russia's war in Ukraine. This means that the model does not account for the REPowerEU plan or other constraints or demands that would encompass the latest, unexpected developments. NVE takes a long-term approach, this means that the large, but short-term fluctuations in energy prices that have hit Norway in the last couple of months are not at the focus of the report. However, with the fluctuations caused by the dynamics between weather conditions and production by renewables, NVE still assesses the price fluctuation expected in the future by looking at the capacities in 2040. Also, the climate policies presented in the EU with high carbon taxes and an increase in power consumption are expected to have an impact on Norwegian energy prices and lead to an increase.

NVE also finds that the future expansion in renewable capacity will to a large extent rely on political will. Renewables like onshore wind are not particularly politically popular, this means that allocating building rights and subsidies can become a problem for future expansion due to the lack of political will. In the future, power production in Europe will shift from fossil fuel-based power production to solar, onshore- and offshore wind. With the increase in renewable energy sources (RES), the demand for improvements in energy storage technologies like hydrogen and battery technologies will also increase. With this, NVE assumes that there will be rapid development in technologies like floating offshore wind, solar photovoltaic (PV), battery technology, and hydrogen, making these options more efficient and cost-effective. With a projected large part of the European energy system being weather dependent in 2040, ensuring sufficient flexibility in the energy system becomes increasingly important. Hydrogen is one proposed solution, however, the technology is not where it needs to be just yet. There are considerable energy losses connected to the production of hydrogen and the production of electricity, from hydrogen. If flexibility solutions like hydrogen or battery technology are not developed fast enough, gas or other types of thermal energy storage might be utilized as strategic reserves. However, this means that when gas is the price-defining power production, marginal costs will increase leading to higher power prices.

NVE's basis scenario is based on current plans for electrifying Norway's transportation and petroleum sector, as well as plans for new industrial activity. NVE's basis scenario projects Norwegian power consumption to increase from 138 TWh in 2021 to 174 TWh in 2040. However, the ceiling might be as high as 200 TWh depending on how many new industry projects will be realized. If the additional consumption from the 200 TWh scenario is realized, a further increase in 10-13 øre/kWh from the base scenario from NVE, which is an average price of 50 øre/kWh in 2040. The analysis estimates a big potential for improving energy efficiency in buildings, reducing consumption by 8 TWh by 2040.

In their scenario, NVE does not introduce new wind. Neither onshore nor offshore, until 2030. For onshore this is because it is currently highly politically unpopular. For offshore wind bureaucratic processes make it doubtful that new capacity will be installed before 2030, this is except for the already announced 4.5 GW located in Utsira Nord and Sørlige Nordsjøen II. It is predicted that power production will increase by 28 TWh from 158 to 186 TWh. The increase consists of 6 TWh from solar PV, 7 TWh from offshore wind, 4 TWh from onshore wind, and 11 TWh from hydro. This gives a power balance of 12 TWh, however with the increase in weather-dependent electricity, these numbers are averages and therefore there will be both export and import of power through the analysis period. However, it is expected that Norway will participate in a more balanced trade with export decreasing and imports increasing [55].

4.4 Statkraft's Low Emission Scenario 2022

For the seventh consecutive year, Statkraft has released their report on a low emission scenario [56]. In prior reports, their goal has been a low carbon scenario that has a max ceiling for the global temperature rise at 2°C. With the geopolitical situation in Europe after Russia's invasion of Ukraine, Statkraft has this year opted for a dual goal. Keeping the temperature limit as in prior years, but also including the goal of a European energy system independent from Russian resources by the year 2030.

The model used for the European pathways in accordance with REPowerEU, is the Statkraft Energy Transition Model. This model is based on GENeSYS-MOD, including 29 European countries. The temporal resolution is the same as the gradual development scenario from openENTRANCE that our dataset is built on.

Statkraft's model finds that it is possible to reach the dual goal of an independent low-emission future, albeit this is very challenging to realize. This is done mainly through clean renewable technologies like wind and solar. The global power demand will have doubled by 2050, wind and solar will supply 2/3 of this demand. Solar power will increase 26-fold in the next thirty years, in today's system that would cover 80% of today's demand. Solar and wind will further increase its competitiveness with fossil fuel technologies and has had a boost in its competitiveness the last year due to the rate of increase in fuel prices being larger than the rate of increase in cost for materials. The system will also become more material-intensive than fuel-intensive in the coming years since solar and especially wind power installations are much more material intensive per installed capacity than traditional fossil-fuel-fired or nuclear power plants. This means that the material supply chains will be increasingly important to secure. There will also be a need for investment in diversification of the production capacity, as there are very few countries extracting the raw materials.

Hydropower shows to become an increasingly important technology for storage purposes. With coal and gas dropping 75% and 23% respectively. Hydrogen is expected to continue to grow, however, Statkraft mentions that the EU's ambitions are extremely ambitious and will be particularly hard to achieve, though still possible. The report finds that all passenger vehicles will be electric by 2050. Annual energy-related CO2 emissions are expected to drop from 32 Gt today to 12 Gt in 2050. Statkraft's report for 2022 projects lower CO2 emissions in 2050 than Statkraft's earlier reports. This shows to be compatible with a temperature increase of 2°C. Statkraft concludes that the dual goal is achievable, however, if it is to be realized action must be taken now [56].

4.5 Gradual Development scenario developed by the openENTRANCE project

The openENTRANCE H2020 project has developed four different scenarios for low-carbon transition pathways for the European energy and transportation system. First, four different storylines that describe a possible development of the European energy system were developed [4] and then quantified into four different scenario datasets [57]. The four scenarios are the following: Direct Transition, Societal Commitment, and Techno-Friendly which all aim for a 1,5°C compatible emission reduction and Gradual Development. The Gradual Development (GD) scenario is the least ambitious and aims at a 2°C compatible future. GD is the most balanced of the four scenarios, lending different aspects of the three other scenarios, with the aim to create a balanced input on active and sustainable citizens, some whole-hearted policy changes, and good technical progress. None of the scenarios is a prediction of the future, they are more to be understood as an exploration of how different combinations of the three aspects (technical progress, citizens engagement, and policy drive) can lead to a more sustainable future. In the scenario, a continuous policy push for reaching emission goals is assumed. As the temperature limit is 0,5°C higher than that of the other scenarios from openENTRANCE, a more moderate carbon pricing could be implemented.

Year	2018	2020	2025	2030	2035	2040	2045	2050
EUR/Tonne	15	30	325	577	830	1184	1492	1800

Table 4.1: Emission penalty in Euro/tonne CO_2 in the openENTRANCE scenario[4].

The underlying storyline for the GD scenario, together with achieving carbon neutrality by 2050 makes it highly relevant for the Ocean Grid project and our work within. Given that the full decarbonization dataset and the modeling framework GENeSYS-MOD are available open source, this scenario has been chosen as the base to build our report.

The geopolitical situation is characterized by geopolitical tension with non-aligned and fragmented international policies regarding the climate. Uneven wealth distribution between countries also contributes to the tension. The resource exploitation to ensure the energy transition is only concentrated in a few regions. The creation of new jobs will be moderate. Low fossil fuel prices will still be important, therefore there will be a need for policy incentives to propose a technology shift. There will be a moderate level of focus on the development of a circular economy. The net effect of the circular economy will be a reduction of GHG emissions. The target for total GHG emission reduction is 70-80% by 2050. Policies that will help ensure that the target is realized are centered on a moderate carbon tax. Still, there are policy developments that give significant support through incentives for acceleration in the required technologies and there is a focus on removing regulatory and administrative barriers for technology diffusion.

Novel technology will be heavily incentivized to ensure the development and research for said technologies. A high focus will be set on making the demand side participate in the climate and energy policies. Due to the lack of novel technologies, the role of existing technology will be immense. For production, this will predominantly be the known RES, onshore/offshore wind, and PV solar. Power-to-X (PtX), gas, nuclear, storage, smart grids, and electrical vehicle (EV) technology are also candidates. The potential for competitiveness is high as the energy system becomes increasingly electricity dominant. The dominance of electricity is both an advantage and disadvantage for the system. The high energy density of electricity makes primary energy demands decrease, however, it also leads to a lack of diversification. With the limited participation of novel technologies, techniques like floating offshore wind will have a limited potential, and still need support. The advantage of supporting floating offshore is that the possible spatial availability for offshore wind increases.

The role of digitalization in energy and transportation will be important. Lifestyle adaptation required from the demand side will be limited and depend on policy incentives. There will be a moderate willingness to pay and invest, and also to unlock demand-side flexibilities. Society’s contribution to the circular economy is moderate. The resources for the energy sector (electricity, heat/cooling, and gas/fossils), will be continued to be built upon, especially RES. Capital will be market driven through both venture capital and incentivized by policies. Transmission and distribution will be improved with smart electricity grids, smart gas grids, and local heat grids. The energy service delivery will improve with increasing support from digitalization. There are only moderate incentives for demand reduction and fuel switching in sub-sectors like industry, commercial/tertiary, and private/building. Mobility patterns will be similar to today's patterns. The demand for individual mobility services will be high and so will the demand for the corresponding infrastructure. From the different types of transportation, aviation will stay fossil-based, however, hybrid solutions will be implemented. Public transportation and private/individual transportation will be electric or hybrid. Maritime and freight will be electric for light-duty vehicles, however for heavy-duty vehicles, they will be hybrid or fossil.

The above-presented storyline has then been transformed into a quantitative scenario dataset for GENeSYS-MOD, which then produced an optimal solution to meet the future demand with the given cost structure of technologies and other constraints. The results of the GD scenario are as expected not as drastic as for the other scenarios. GD results show that non-mature technologies are not deployed[58]. An example of this is CCS and direct air capture. The biggest additions to the European energy system towards 2050 would be in PV, offshore and onshore wind. There is a reduction of almost 50% for primary energy demand. Oil and gas play an important role in the system until it is started to be phased out from 2040 to 2050 and carbon neutrality is reached by 2050. The electricity sector is carbon neutral by 2040. This is because the phase-out of coal will be very rapid, and done by the year 2030. With the increase in renewables, hydro and nuclear will provide baseload capacity. Nuclear will be located predominantly in France and Eastern European countries. Even with the additions of heat pumps, natural gas-based heating systems will still be present in residual heating by 2050, this means that the heating sector will not be fully decarbonized. In industrial heating, there will still be coal until 2045. For transportation, low carbon technologies will be present for both freight and passenger transportation, with freight being handled predominantly with hydrogen trucks and electric rail, while passenger transportation will consist mostly of battery electric vehicles (BEVs). For the whole system, decarbonization is almost done by 2050. Thus making it the most coherent scenario with current national and international policy targets.

Chapter 5

Development of the Nordics and North Sea zero emission scenario (NNSzero)

The main objective of the Ocean Grid research project, in which this project is embedded, is to analyze the impact of one or more offshore bidding zones in the North Sea and how this affects the profitability of offshore wind power. The aim of this master thesis is to develop a data set for the Nordic and North Sea countries for a decarbonization scenario (NNSzero) for the energy system model GENeSYS-MOD and to test the implementation of an additional offshore bidding zone. This is a first step to better represent the future development of the Norwegian energy system in GENeSYS-MOD. This chapter describes all steps taken.

The NNSzero dataset is based on the gradual development scenario created by the openENTRANCE H2020 project [57]. In the master thesis ”Modeling Multi-Sectoral Decarbonization Scenarios for the Norwegian Energy System” [59], Norway was disaggregated into five nodes, representing the five power price regions of the Norwegian power market. In the base case scenario, four out of the five nodes incorporate offshore areas, accommodating offshore wind development. The disaggregated Norwegian data has been further refined in the Nordic Energy Outlook program WP1 and WP2 [60, 61]. For European countries, the openENTRANCE project provided an updated dataset that was utilized [62] and combined with the disaggregated Norwegian dataset. Furthermore, the disaggregation of Denmark was executed with the aim of enhancing the dataset's spatial resolution accuracy and improving the precision of trade connections related to a North Sea offshore node. Data for population, spatial resolution, demand, trade, and capacity to disaggregate Sweden was also collected, but not implemented into the model in this thesis. The collected data for Sweden can be found in the appendix **??**. Multiple European countries were removed from the dataset in order to avoid run time challenges when working with a high-resolution Nordic and North Sea dataset and to limit the amount of data that needs handling and error-proofing. The countries currently included in the model are Austria, Belgium, Switzerland, Czech Republic, Germany, Denmark, Estonia, Finland, France, Spain, Ireland, Lithuania, Luxembourg, Latvia, Netherlands, Poland, Sweden, United Kingdom, and Norway. // The changes mentioned above contributed to the forthcoming publication of the paper ”Large-scale Offshore Wind Development and Decarbonization Pathways of the Norwegian Energy System”[49]. This paper looks at the optimal capacity expansion and energy dispatch in GENeSYS-MOD when Norway is divided into bidding zones with and without an offshore node in the North Sea.

5.1 Creating the Nordics and North Sea zero emission dataset

This chapter describes the creation of the Nordics and North Sea zero emission dataset (NNSzero). The process includes changing the geographical resolution to focus on the Nordic and North Sea countries. Norway and Denmark have been disaggregated based on Nordpool's bidding areas. The dataset is then split into two subsets: with and without an offshore node in the North Sea.

5.1.1 Geographical resolution

When additional regions are added to the model, the complexity and hence computational time increases. The original openENTRANCE model encompassed 30 European countries/regions and was solvable with a temporal resolution of 122 hours per timeslice. This is without the disaggregation of Norway and Denmark, and the addition of an offshore node. In order to limit computing time as the complexity increases, countries not bordering the Nordics or the North Sea countries were removed. This left 19 countries, 24 nodes when Norway and Denmark are disaggregated, and 25 with the addition of an offshore node in the North Sea.

Figure 5.1: Nordic and North Sea countries highlighted in green, neighboring countries highlighted in blue.

While the removal of these countries may not have led to a noticeable impact on capacity expansion in the North Sea countries and the Nordics, it is important to consider the potential consequences of excluding such countries from the model. By removing distant countries, we might overlook potential interdependencies that could influence capacity expansion and energy trade in the region. To check if the model produced reasonable results each time a country was removed from the dataset, the Spanish solar capacity was compared to previous values with all countries included. Spain was chosen as the reference since the model depends heavily on renewable energy growth in Spain to meet the rising demand for energy. This is mostly due to Spain's large area and good conditions for PV development. So if a removed country substantially affected the output of the model, one such initial indication would likely be an observable change in capacity values in Spain.

The model yielded infeasible results if countries were removed in the wrong order, making it impossible to meet the energy demand. For example, the removal of Hungary and Slovenia prior to Croatia disconnected Croatia from the main European power grid, rendering it impossible to find an optimal solution for the program. In a similar vein, removing Spain from the model would render the problem infeasible due to its significant impact on Europe's reliance on Spanish solar power. The model could not find a solution to meet demand without Spain.

5.1.2 Trade

There are five trade sheets in the input data set containing information about the trading of fuels between regions. The five trade sheets are Trade routes, trade costs, trade capacities, trade capacity growth costs, and the rate of growth for trade capacities. The last two sheets are equal for all regions so they could just be copy pasted for any new node, Trade capacity growth costs provide the costs of expanding trade capacity in $M\frac{E}{GW}$, while the growth rate for trade capacities provides a factor for how much capacity can expand between two regions. There was no detailed information available in the model or dataset description on how the current data sets had set up the trade routes. However, taking the geographical center of each country and measuring the distance to connecting nodes is a common practice in state-of-the-art energy system models, and was utilized for new trade routes. If there is no possibility for direct trade between regions, the route is set to 0, otherwise, the value is the length of the line in km. The trade costs are then calculated based on the length of the trade route. There are four different Excel formulas for the trade costs, these are provided in the openENTRANCE dataset and are used to calculate the costs of different fuels. The trade capacities are pipeline capacity for gas and transmission capacities for power. The values of the transmission capacities for power between the Scandinavian bidding zones were gathered from Agency Cooperation Energy Regulators (ACER) [63]. The trade-related sheets are all big datasets with a large number of data points. This, with a lack of automatization for data insertion in the dataset, introduces a risk of errors in the dataset, when introducing new regions.

5.1.3 Adjusting capital investments costs

The initial implementation of the new offshore region, OFF_NO, resulted in artificially high capital investment costs primarily due to the inclusion of grid expansion expenses. Grid expansion costs are already included in the capital investment costs for offshore wind technologies in the openENTRANCE scenario. As OFF_NO is situated in the North Sea, additional costs were incurred for grid infrastructure development. This distinction sets OFF_NO apart from other regions within the GENeSYS-MOD model, where offshore wind power is typically located onshore, eliminating the need for grid expansion and avoiding double grid expansion costs.

By conducting a literature study in offshore capital investment costs 2.3, efforts were made to correct this double grid expansion cost for the OFF_NO region. The paper "Offshore wind-turbine structures: a review" [46], suggests that grid connections represent 15%-30% of total costs for offshore wind power. Since RES_Wind_Offshore_Deep is offshore wind technology with the highest cost in the model originally and has a higher grid expansion cost included in the original capital cost. Therefore this technology received the highest possible cost reduction possible in accordance to [46]. The other offshore wind technologies were also reduced as shown in table 5.1.

Technology	Old cost	Reduction factor	New cost
RES_Wind_Offshore_Transitional	3500.00	0.85	2975
RES_Wind_Offshore_Shallow	2975.00	0.77	2290.75
RES_Wind_Offshore_Deep	4025.00	0.7	2817.5

Table 5.1: Capital cost of Offshore Wind Technologies (Million Euro/GW).

There are a lot of uncertainties connected to this adjustment of capital costs for offshore regions. The paper [46] only compares four wind farms. This is the reason for the large deviations between the lower (15%) and upper (30%) bound and lower bound of the percentages. These wind farms are also all from the early 21st century. This means that the numbers might have changed considerably over the past 20 years. Thus this paper might not be ideal to base the future update of prices.

5.2 Disaggregation of the Nordic countries

This chapter describes how Denmark and Sweden have been split into several regions based on the geographical scope of the Noordpools bidding areas [64]. Sweden consists of four bidding zones, while Denmark has two. GENeSYS-MOD has techno-economic data for parameters and specific time series for demand and variable renewable energies. The current demand for Denmark and Sweden needs to be divided between the bidding zones and input into the dataset. This includes demands detailed into heating, transportation, and electricity, as well as base year installed capacities and production values. Note that the time series for each technology stays the same, it is only the value for demand that is changed. The time series for weather data needs to be changed for each geographical area in order to represent wind and solar conditions.

5.2.1 Disaggregating Denmark

Denmark has previously been represented in GENeSYS-MOD as one region. In order to enhance the representation of the energy system, Denmark was disaggregated into its bidding zones, which are determined by Nordpool[64]. These bidding zones provide a more accurate and granular depiction of the energy system within Denmark, allowing for a better understanding of regional variations and facilitating more precise analysis and modeling. It consists of two regions, DK1 and DK2. Data on Danish energy consumption, production, and population already exists in the scenario data and come from the OpenENTRANCe project[4]. There are seven categories for demand in GENeSYS-MOD. Four of these are based on population: Power, Mobility freight, Mobility passenger, and Heat low residential. The other three: Heat low industrial, Heat medium industrial, and Heat high industrial are based on the industry in each area. The disaggregation of Denmark does not require new data for each specific region. Instead, it involves identifying suitable factors that can be used to distribute the initial data accurately among the different regions. These factors are determined by population and industry.

DK1 is often referred to as West Denmark. It consists of the North, Central, and Southern Denmark, while DK2 is often referred to as East Denmark and consists of Region Zeland and the Capital Region of Denmark [65].

Figure 5.2: Danish bidding zones.

The data on the population of Denmark and the area for each bidding zone was acquired from Statistics Denmark [5]. Denmark has 5.87 million inhabitants. By looking at the population in each county, then summarizing all counties in each bidding zone, one sees that the population is fairly evenly distributed between DK1(3158643) and DK2(2708769), as shown in table 5.2.

Bidding zones	Population	Area [km2]	Industry share
DK1	3158643	33161.4	65%
DK2	2708769	9789.7	35%

Table 5.2: Danish population, area and industry share for DK1 and DK2[5][6].

Heat low, medium, and high industrial does not depend on population but rather the location of large industries. By contacting the Danish Energy Agency, Energistyrelsen, an Excel document was obtained containing power consumption data for two different sectors: private households and business life **??**[6].A large portion of business life energy consumption is already covered in previous categories for demand, like Power and Mobility freight, which depend on population. So the "Business life" category is a lot broader than just the industrial sector. Even so, this was used to get an approximation of the shares between DK1 and DK2. DK1 has a lot of energy intensive industry, and this shows in the business life numbers, using 12 722 GWh, compared to DK2 which used 6 848 GWh. This gives the share presented in table 5.2.

5.2.2 Disaggregating Sweden

Similar to the approach taken for Denmark, the intention was to disaggregate Sweden into its corresponding bidding zones to enhance the accuracy and realism of the energy system model. Extensive efforts were made to collect the necessary information and data required for the disaggregation of Sweden into SE1-SE4 bidding zones. However, due to time constraints, the implementation of this data into the code was not completed, and therefore, the current results of this thesis do not reflect the disaggregated model for Sweden. Nevertheless, this groundwork and collected data can provide valuable insights and serve as a foundation for future master students or for Sintef to further refine and expand the energy system modeling efforts.

5.2.3 Weather data

Offshore wind, onshore wind, and photovoltaic energy production is represented in GENeSYS-MOD through hourly time series. All countries have region-specific time series which are based on the geographical area and climate. DK has been split into two separate regions with different climate conditions, necessitating the generation of new time series for each region.

Wind series

GENeSYS-MOD has three different technologies for offshore wind: Wind_offshore, Wind_offshore_shallow, and Wind_offshore_deep. Wind_offshore_shallow is equivalent to 85% of the Wind_offshore series from the openENTRANCE project. Wind_offshore_deep has significantly higher per unit values than Wind_offshore_base, reaching 0.63 average wind yield each hour compared to 0.42 for Wind_offshore. The different wind categories in GENeSYS-MOD also have different distances from shore in addition to wind time series. 9 km or closer is offshore shallow, 9 km to 27 km is offshore transitional and anything above 27 km is considered offshore deep. In the openENTRANCE project, a systematic approach is employed whereby points are mapped at predetermined distances from the shoreline, followed by the determination of their respective countries. A similar methodology can be applied to achieve sub-country resolutions.

There exist multiple approaches to obtaining wind series. One viable method is to generate new time series based on historical data. An invaluable tool for such simulations is renewables.ninja[66], a software utility that enables users to simulate the hourly output of solar and wind power for any geographical location worldwide. This resource draws upon the NASA MERRA reanalysis and CM-SAF's SARAH dataset as its foundational data sources[67][68].
To generate two new time series representing onshore wind and photovoltaic power production, the geographical centroid of regions DK1 and DK2 was utilized. The coordinates of existing offshore wind farms within both regions were employed for offshore wind.

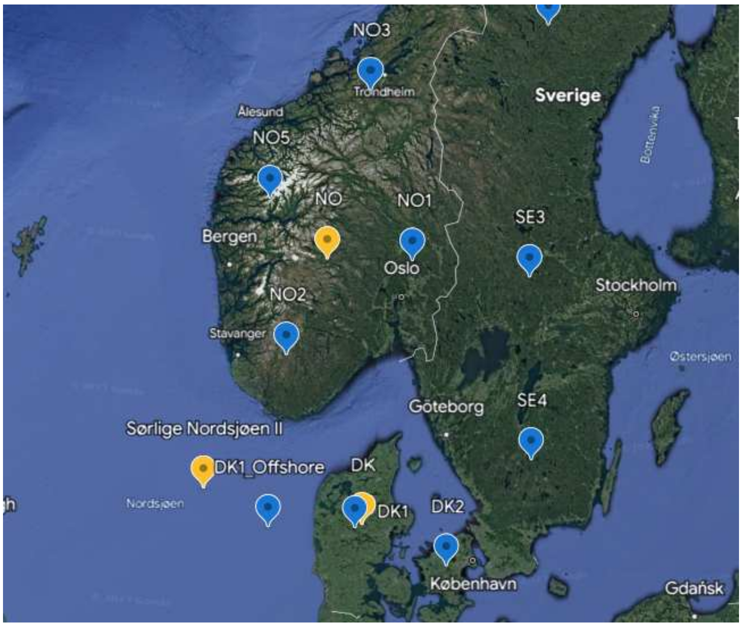


Figure 5.3: Overview of locations used for weather data and trade.

The hourly time series from renewables.ninja presented significantly higher per unit average values for the DK1 and DK2 regions than what openENTRANCE had for DK. Wind_Onshore_Base for DK had an average of 0.28 each hour while renewables.ninja gave DK1 an average power production of 0.38, an increase of 36%. The geographical centroid of these locations is not that far apart and it is unlikely that the location impacts the results that much. The same increase was seen in offshore values and all other locations that were tested. This resulted in a large expansion of onshore and offshore wind capacity in GENeSYS-MOD when running with the renewables.ninja time series. This approach results in inconsistent wind profiles when compared to other wind series in the model. Alongside the use of renewables.ninja, to ensure the accuracy of the results, the obtained outcomes were compared to weather data from the ECMWF Reanalysis v5 (ERA5) dataset[69]. Sintef developed a program that uses the ERA5 weather dataset and creates hourly wind series for a specific geographical location based on ERA5 [70] [71].

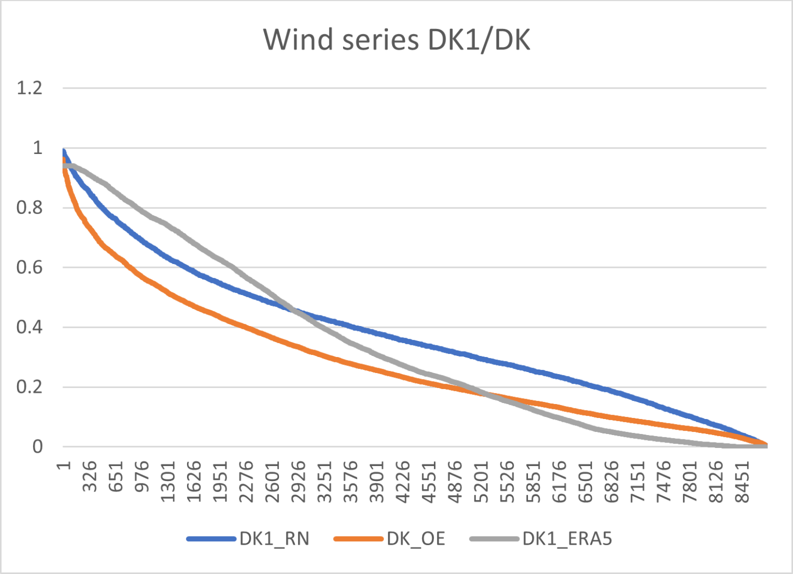


Figure 5.4: Comparison of openENTRANCE, renewables.ninja and ERA5 wind series.

Three wind series options are available for the new disaggregated regions, and the choice of which one to use significantly impacts the results and capacity expansion within the model. Upon analyzing the data, one notable observation is the substantial difference in average values across the three options. The box plot 5.5 illustrates that the openENTRANCE wind series exhibits the lowest total amount of wind power production. Additionally, the distribution of power production also varies among the options. Both openENTRANCE and renewables.ninja has fewer hours with high wind power production compared to ERA5, seen in figure 5.4, which demonstrates more hours of both high and low wind power generation,

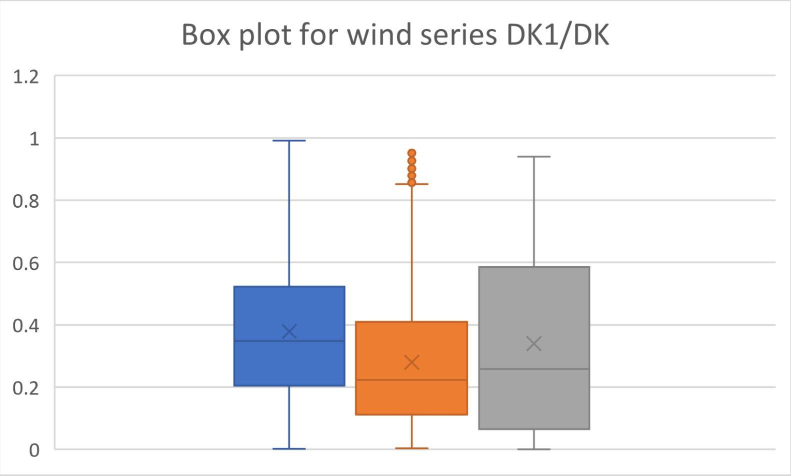


Figure 5.5: Box plots for the wind time series

which would increase the energy price volatility[72].

As the project deadline approached, the openENTRANCE wind series generation code was obtained, but limited time prevented the generation of additional time series using this tool. Consequently, all three methodologies for generating wind time series were explored, and significant differences were observed that influenced the results. Further investigation into each methodology in detail would be a recommended next step, considering the impact on the outcomes.

Ultimately, the outcomes generated by GENeSYS-MOD exhibited notable disparities when utilizing renewables.ninja or ERA5, in contrast to runs conducted with openENTRANCE wind series. The substantial increase in average hourly wind in these two cases resulted in a corresponding rise in onshore and offshore wind capacity, consequently replacing other technologies such as photovoltaic (PV) systems. These disparities were of such magnitude that they posed challenges in investigating the impact of Denmark's disaggregation, the introduction of an offshore node, and the manner in which the offshore node was interconnected. Given that all other regions were modeled using openENTRANCE wind series, this approach emerged as the preferred solution within this study. Consequently, the newly established DK1 and DK2 regions adopted identical time series as DK. This is not optimal, but not necessarily that significant. Wind series from renewables.ninja showed very similar values for DK1 and DK2. This could be improved in future work.

5.2.4 Adjusting the Norwegian dataset

A new capital cost should be set for the offshore wind technology in the offshore node. The cost of offshore wind includes the cost of transmission capacity. When configuring the model with offshore nodes the model will build actual transmission capacity between the offshore node and other regions, thus the price should be lowered. The capital cost has been lowered between 15 and 25 percent based on the ICE repport discussed in chapter two[]. The gradient is set to represent how the prior cost has been set. Shallow is based on 9km from shore, transitional is 9 to 27 km and deep is anything above 27. Offshore deep is therefore reduced the most. Under are the factors used for the new costs.

The Norwegian dataset had been disaggregated into bidding zones NO1-NO5 in a previous master thesis[59]. When disaggregating Denmark, this was used as a guideline in order to keep the implementation consistent. Due to a lack of data, in the previous master thesis, the industrial demand was disaggregated according to agricultural production in each bidding zone[7]. In this report, Industry and Agriculture were displayed in the same subsection and therefore used to approximate industry shares. This misplacing of Industry might lead to the wrong base year production and residual capacity. The annual demand for each area will also be incorrect which affects capacity expansion and production in the model. In order to get results with higher accuracy this needed to be corrected. NVE was contacted regarding this matter and granted access to documents containing energy consumption data for different sectors and bidding zones. This data was gathered from Statistics Norway [8]. Comparing old and new data in table 5.3 shows some differences, not as great as first anticipated, but still a small improvement of the disaggregated dataset for Norway.

5.3 Contributions to the paper

During the course of our master's thesis, the idea of adding an offshore node in Norway was initially explored and presented as an article titled ”Large-scale Off-

Bidding zone	Previous industry share	New industry share
NO1	5%	10%
NO2	28%	34%
NO3	32%	27%
NO4	19%	14%
NO5	17%	15%

Table 5.3: Norwegian energy consumption by industry divided into bidding zones by old [7] and new shares [8].

shore Wind Development and Decarbonization Pathways of the Norwegian Energy System." in the 19th Conference on the European Energy Market Under the leadership of Dana Reulein. The article investigated optimal capacity expansion and energy dispatch in two distinct cases using the GENeSYS-MOD framework. The first case involved disaggregating Norway into five bidding zones, while the second case introduced an offshore region for offshore wind generation connected to NO2. This research focuses on investigating a policy of the Norwegian government (30 GW wind) and improving the dataset by incorporating Norwegian industry and capital expenditure data. Additionally, the research determines the optimal pathway under given constraints, building upon the pathway outlined in the conference paper. Furthermore, the disaggregation of Denmark into bidding zones was carried out as part of this study.

In terms of our contribution to the paper, the groundwork during our specialization project formed the basis for both the paper and this Thesis. Here, we have provided an improved dataset with Norway industry, CAPEX, and determined the optimal pathway under given constraints. The paper is included in its entirety in the Appendix 7.2.

5.4 Observations and inaccuracies

During the process of updating an energy system model, the stage of refinement and improvement ensures the model's accuracy and applicability to real-world scenarios. It is common to encounter a range of errors, difficulties, and problems during this process. It is important to acknowledge that such updates can be complex and may involve unforeseen challenges that need to be addressed. This section aims to highlight and discuss problems and difficulties that arose when updating the dataset. Understanding and addressing these issues gives valuable insight when analyzing the results or updating the model further.

The ”Power” demand is currently based on population alone, but ”Power” cover both residential power demands and industrial demands. This makes the power demand in areas with a lot of industry artificially low, while the densely populated areas get a power demand that is too high. Correcting this is possible by comparing the industrial power consumption against the residential power consumption in each bidding zone. This is certainly possible but would differentiate from how NO1-NO5 was disaggregated in the master thesis ”Modeling Multi-Sectoral Decarbonization Scenarios for the Norwegian Energy System” [59], therefore this is not a priority. ”Mobility freight” is also based on population numbers alone. This category is certainly affected by industry locations as well, but this is not accounted for either.

The determination of new shares for demand in each bidding zone relies on accurate data published by national energy agencies, reflecting real demand and aiming for the highest possible accuracy. However, incorporating this new and improved dataset poses a new challenge. While it enhances the accuracy and reliability of the data, it creates a disparity between the disaggregated countries and the other countries in the model, which use the openENTRANCE demand data. Furthermore, modifying the base year values could lead to compilation errors if the values do not represent a valid system. In order to manage the workload and address these complexities, the decision has been made to maintain the total demand as presented in openENTRANCE and allocate the demand among bidding zones based on their respective shares of this dataset.

During the model updating process, both the implementation of CO2 penalties and CO2 limits in accordance with the EU Fit for 55 guidelines[73] were explored. The necessary groundwork and data collection were carried out to incorporate these options into the model. Initially, the model successfully transitioned to incorporate CO2 limits at the 1000th timestep, and it appeared to be functioning well. However, when attempting to reduce the timestep further, computational challenges arose in finding a viable solution within the constraints of CO2 limits. It became evident that achieving runs at lower timesteps with the CO2 limits configuration would require additional adjustments. As the focus of the report was not specifically on addressing these challenges, the decision was made to revert back to using CO2 limits instead of penalties. The final timestep resolution was 400 hours per timeslice. The data and information related to changing from CO2 penalties to limits are included in Appendix**??**. Improving temporal granularity to enable the use of penalties could be considered future work.

Chapter 6

Results and Discussion

The research conducted in this thesis has generated the necessary results to address the research questions outlined in the introduction. This chapter specifically focuses on presenting and discussing the results related to the two research questions.

- The first research question: To investigate whether the disaggregation of Denmark into bidding zones has a meaningful impact on the energy system or if it is negligible. For the first research question, the following results are presented:
  - Installed capacities for power generation
  - Emissions
- For the second research question: What is the cost-effective grid expansion strategy from the Norwegian offshore wind area to the neighboring countries around the North Sea? For the second research question, the following results are presented:
  - Evaluation of installed capacities
  - Assessment of transmission capacity
  - Analysis of power generation

  - Investigation of power import and export
  - Examination of the marginal cost of power production

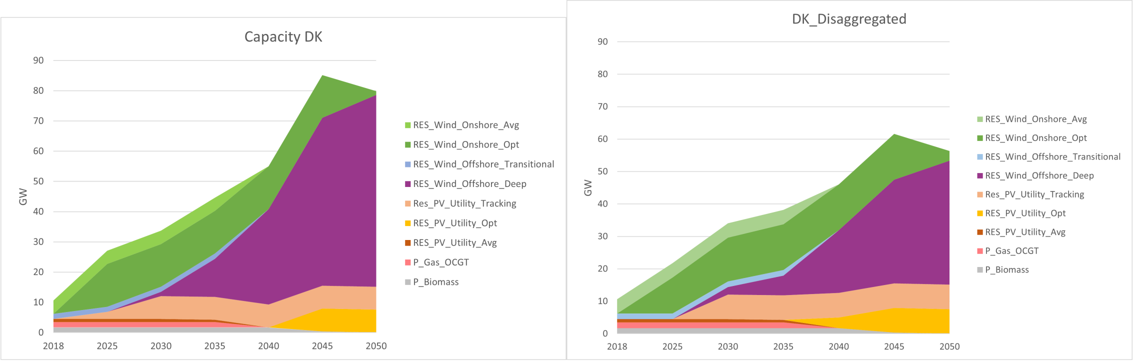
6.1 Disaggregation of Denmark

The disaggregation of Denmark into its bidding zones aims to analyze its impact on the power sector. This investigation involves two distinct case studies:

- Base Case: This case features the disaggregation of Norway while the rest of the data is from the openENTRANCE scenario, Denmark is considered as one single region, and there is no offshore node.
- Disaggregated Denmark: The dataset is the same as in the base case, however, Denmark is disaggregated into its two bidding zones.

6.1.1 Installed Capacity

The following plots show the installed capacities in Denmark for the base case and disaggregated Denmark scenarios. Lastly, the split for DK1 and DK2 in the DD case is displayed.



(a) Capacities in Denmark for the base case.

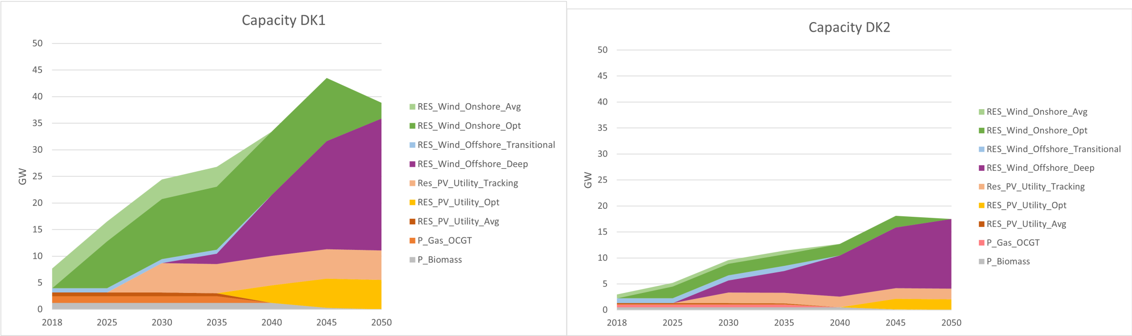
(b) Capacities in Denmark disaggregated

Figure 6.1: Capacities in DK and DK_disaggregated

Figure 6.1a displays installed capacities for the base case. The results show a capacity peak in 2045 with a total installed capacity of 85.6 GW before dropping to 79.9 GW in 2050. The majority, 79.5% of the installed capacity in the base case is deep offshore wind technology. Onshore wind is prevalent until 2045 before it tapers off in 2050. The rest, 18.9%, of the energy mix, is made up of photovoltaic. The trend for overall growth is rather linear, however, the capacity expansion of offshore wind, is that of exponential growth until its peak in 2045.

Figure 6.1b shows the installed capacities for the disaggregation scenario. The nodes DK1 and DK2 were combined to display the total installed capacities for Denmark. The total capacity peaks in 2045 at 67 GW, afterwards it decreases to 62.3 GW in 2050. The majority, 69.1%, of the installed capacity, is deep offshore wind technology. Onshore wind will be a big part of the energy mix until 2050 when the percentage decreases. Photovoltaic technology makes up the rest of the energy mix, 24%,. The total capacity of PV technology is almost constant from 2030 to 2050. The general trend of the capacity expansion is a linear increase in RES capacity until its peak in 2045, while non-RES technology is phased out by 2040.

From the results in Figure 6.1 it is clear that the effect of disaggregating Denmark into its bidding zones is quite significant. There is a 21.7% decrease in total capacity in Denmark's capacity peak in 2045 from the base case to disaggregated Denmark. Both case studies experience a drop in total capacity from 2045 to 2050. One reason for this can be the lifespan of onshore wind, which is set to 21 years in the input data. This means that some onshore wind in Denmark is phased out between 2045 and 2050. To understand the drop in total installed capacities between the cases, more results for the disaggregated case must be studied. Firstly, the difference in capacity between DK1 and DK2 is represented.



(a) Capacities in DK1 for the disaggregated scenario

(b) Capacities in DK2 for the disaggregated scenario

Figure 6.2: Capacities for DK1 and DK2 in the disaggregated Denmark scenario.

Figure 6.2 shows the capacities of Denmark split into its two bidding zones. Both regions display a very similar expansion trend and energy mix to the base case in Figure 6.1a. The share of offshore wind in DK2 is slightly higher than that of DK1. The majority of capacity in Denmark is located in the western region, DK1, 68.5% of the installed capacity is located there.

In the input data, the specified demand for DK1 and DK2 is very similar. Power demand is 42.6 PJ compared to 36.6 PJ respectively in 2050. So the difference in installed capacity between the regions is not due to demand differences. If power import/export is studied the answer may be found.

Country	Type	2018	2025	2030	2035	2040	2045	2050
NL	Import	109.48	213.53	235.79	247.13	274.10	319.24	313.52
NL	Export	-12.85	-40.25	-58.94	-95.15	-134.48	-168.55	-183.53
DK	Import	116.67	119.20	138.03	89.70	74.08	68.11	74.29
DK	Export	-119.24	-182.80	-230.11	-354.17	-603.90	-844.01	-956.70

Table 6.1: Power Import/Export in PJ for the basecase

Country	Type	2018	2025	2030	2035	2040	2045	2050
NL	Import	93.23	180.19	211.48	197.31	193.80	198.78	190.35
NL	Export	-13.66	-41.33	-54.08	-87.58	-132.15	-162.05	-187.34
DK1	Import	21.87	20.37	21.91	21.18	11.89	13.18	14.47
DK1	Export	-39.64	-62.86	-88.30	-124.66	-224.25	-344.77	-404.70
DK2	Import	34.43	35.66	27.09	19.02	14.02	12.92	23.09
DK2	Export	-21.83	-26.16	-46.55	-64.17	-102.21	-138.71	-160.18

Table 6.2: Power Import/Export in PJ for the disaggregated case

Table 6.1 and 6.2 presents the power import and export for the regions NL and DK in the base case and NL, DK1, and DK2 in the disaggregated Denmark case. Import is positive values while export has negative values. From the tables it is clear that the disaggregation has a substantial effect on export for Denmark. There is a significant difference in Danish export for the base case and disaggregated Denmark. The export of power is 956.7 PJ to 564.9 PJ in 2050 respectively. The export for the disaggregated Denmark scenario also includes trade between them, however, the total import is only 37.56 PJ, so for the purpose of detecting a trend, it is negligible. With export declining for Denmark, the import to other regions will also decrease. In this case, the Netherlands is investigated. The import decreases by 39.3% from 313.5 PJ to 190.35 PJ. Meanwhile, the installed capacity in the Netherlands increases from 67.2% GW to 75.2 GW to compensate for the lower import, as export stays almost identical.

The reason the cost-optimal solution changes when Denmark is disaggregated can be divided into three main reasons:

- Trade connections accuracy: When disaggregating regions, points of fuel trade can be more accurately set.
- Reduced total annual maximum capacity: In the model input data specified annual demand is set, when a region is disaggregated, the total annual maximum capacity is split among the new regions.
- Structural Congestion: One of the reasons bidding zones are introduced into electricity markets is to detect structural congestion. If a power system has a bottleneck due to insufficient transmission capacity, zonal disaggregation can be utilized for congestion management[74].

The reason for the capacity drop is thus as follows: The power trade connection between Denmark and the Netherlands is located in western Denmark. The total annual maximum capacity of DK1 in DD is lower than that of DK BASE, which is a result of Denmark being disaggregated. Structural congestion is introduced to the Danish power system with a transmission capacity of 600 MW between Zealand and Fyn being represented in the model. This means that when the Netherlands and Denmark trade in the disaggregated case, the Danish region connected to the Netherlands, DK1, has less capacity to build out and is reliant on another node, DK2, which introduces a bottleneck to the system. The cost-optimal solution for the model is therefore to build less capacity in Denmark and locate it elsewhere.

6.1.2 Emissions

This section focuses on the analysis of emissions in GENeSYS-MOD, comparing the base case scenario with the disaggregated Denmark scenario. The aim is to assess the potential impact of disaggregation on CO2 emissions and evaluate any visible differences between the two scenarios.

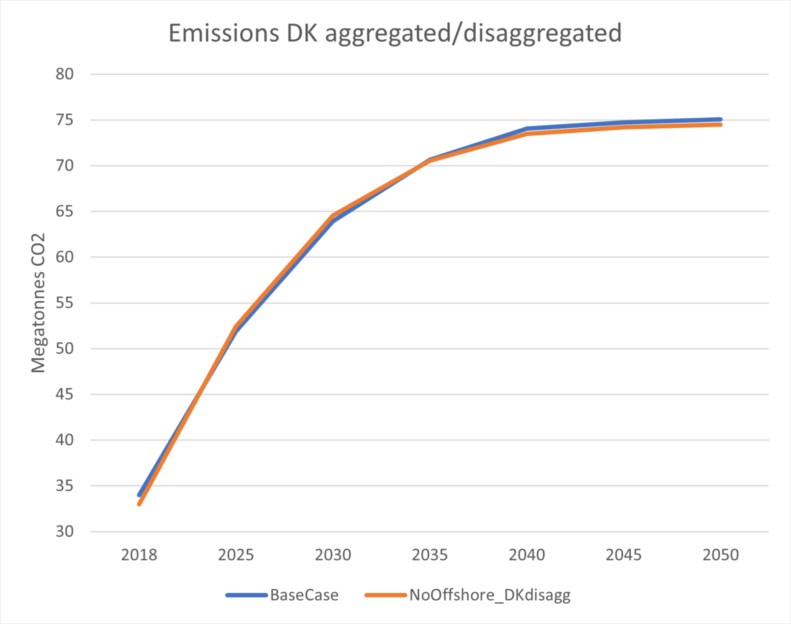


Figure 6.3: Emissions for DK aggregated vs disaggregated.

The emissions depicted in Figure 6.3 represent the cumulative emissions in Denmark from 2018 to 2050. It is noticeable that the emissions start at slightly different levels. However, it is important to highlight that the two scenarios closely track each other throughout the scenario analysis. Notably, the disaggregated Denmark scenario shows a reduction of 0.6 megatonnes in CO2 emissions compared to the aggregated scenario. Such a small difference between the two scenarios may indicate that the disaggregation has little to no effect on emissions, only differentiating 500 000 tonnes of CO2, which is less than one percent of the total emissions.

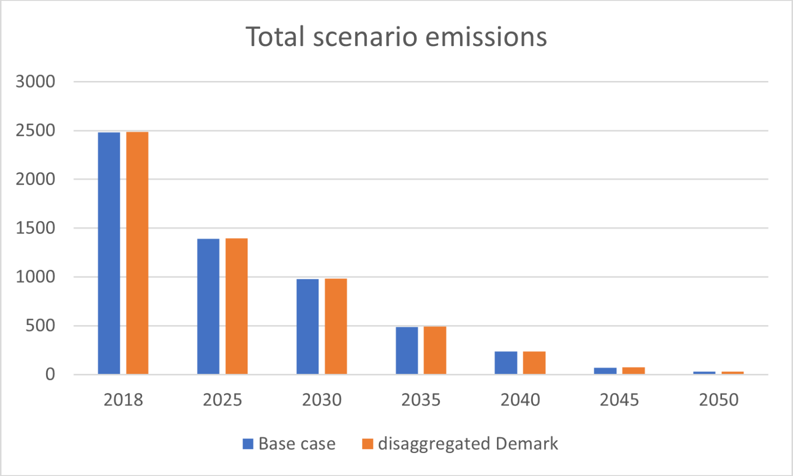


Figure 6.4: Total emissions for the base case and disaggregated Denmark scenario.

The total scenario emissions also stayed similar 6.4. The trend is the same; the disaggregated Denmark scenario started with slightly higher emissions, and in the end, emitted 0.3% more CO2, 5667 million tonnes compared to 5683 million tonnes. It is difficult to say if this is a mistake in the input data or a consequence of Denmark's disaggregation. One explanation might be that the additional DK region introduces more trade and trade losses, which would result in more production and emissions.

6.2 Introduction of an offshore node

Three runs were modeled to investigate the effect of the grid configuration of the introduced offshore node.

- Run 1: Offshore node, Disaggregated Norway, Disaggregated Denmark, Possible offshore connection to NO2
- Run 2: Offshore node, Disaggregated Norway, Disaggregated Denmark, Possible offshore connection to NO2 and DK1
- Run 3: Offshore node, Disaggregated Norway, Disaggregated Denmark, Possible offshore connection to NO2, DK1, and UK

For brevity and legibility in this section, The cases will be referred to as run 1, run 2 and run 3 in accordance with the bullet points above. The results presented below are as follows: the installed capacities of the offshore nodes, NO2, DK1, and UK, the transmission capacity expansion for the connections to the offshore node, power production in DK1 and power import/export between the countries, and finally a look at the marginal cost of power in the last timestep for the last year in relevant regions.

6.2.1 Installed Capacities

When performing the three runs, multiple plots were created for each region for every run. Without showing all results, this section will highlight the most important ones that contribute to the analysis.

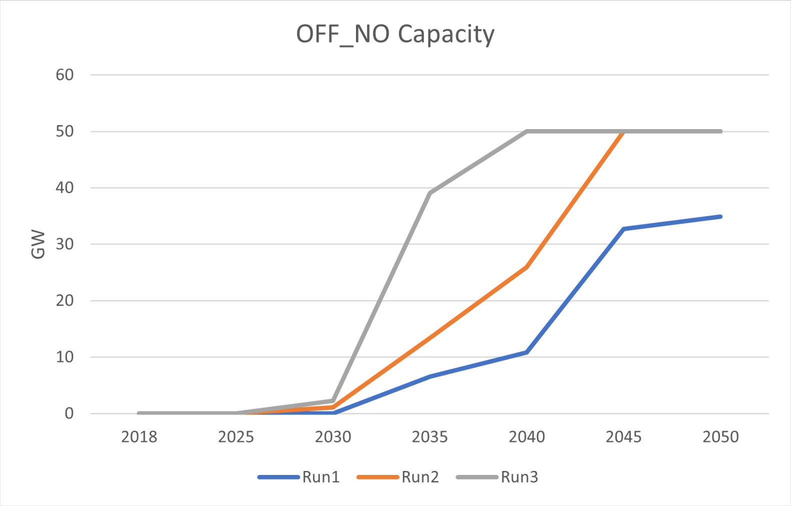
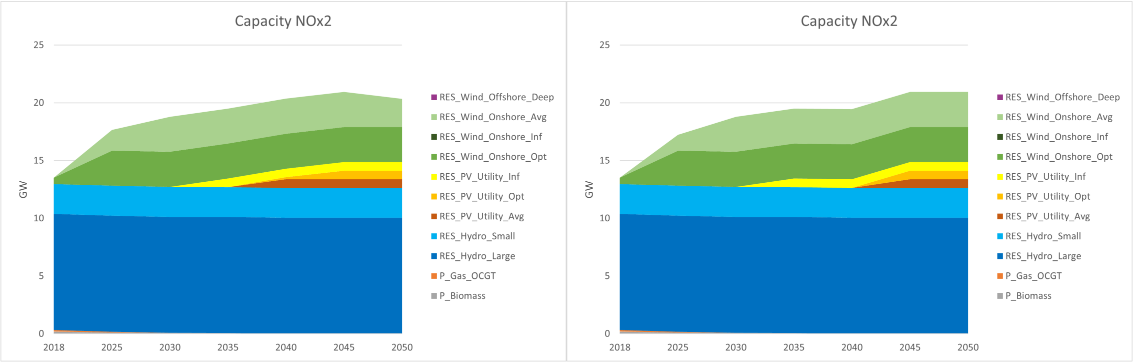


Figure 6.5: Capacity expansion for the offshore node with different grid solutions.

The only technology present as installed capacity in the offshore node is the deep offshore wind technology. This is the most expensive form of offshore wind technology, however, it also yields the most favorable wind conditions. The graphs illustrate that the more the node is interconnected with the surrounding regions the more capacity it builds. There is an upper bound set at 50 GW of offshore wind which the model reachers in run 2 and run 3, as seen in figure 6.5. The upper bound is set in regard to the Norwegian plans for 30 GW of offshore wind expansion [2]. In preliminary results, this upper bound was reached in all runs, a higher upper bound of 50 GW was therefore set to allow the model to display different trends, For run 1 the node can only transport power to the NO2 region the installed capacity peaks at 35 GW in 2050. In run 2 the model reaches its ceiling of 50 GW in 2045 after a linear increase from 2030. In run 3 the model has a drastic increase of 35 GW over a five-year period between 2030 and 2035, and the model reaches the cap in 2040.

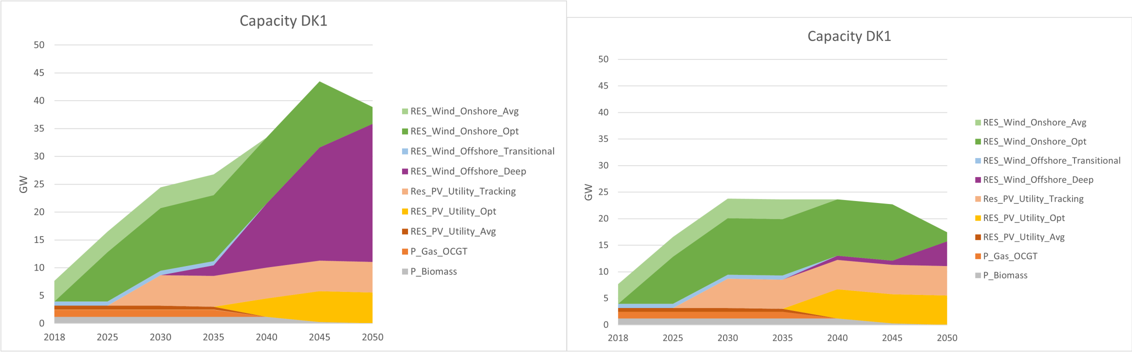
The results clearly demonstrate that the cost-optimal solution for the model is to increase offshore wind capacity in the offshore node as the number of connected regions expands. To illustrate this the total capacity over the entire time horizon can be studied. These numbers are only used to display the difference in impact. For run 2 the offshore node has a total capacity of 140,7 GW over its time horizon, while for run 3 the total is 191,3 GW. This is an increase of 36%. This result matches ”Fagrapport om havvind i Sørlige Nordsjø II” which also the biggest market surplus when connecting the Sørlig Nordsjø II wind park to UK and DK [10]. More results will be presented to provide a better understanding of the reasons behind these findings.



(a) Capacities in NO2 for run 1 **(b)** Capacities in NO2 for run 2

Figure 6.6: Capacities for NO2 for run 1 and 2.

Figure 6.6 presents the installed capacities in the southernmost Norwegian bidding zone NO2, which is connected to the offshore region. The results clearly show that the grid connection barely affects the capacity levels of NO2. The only difference is that the more connected scenario in run 2, optimal and average PV technology is built in 2040 rather than in 2035. The reasons will become clear when power trade and trade capacities are presented later in this chapter. One observation of the results is that the capacity of hydropower is constant in both cases. This is due to a limitation of GENeSYS-MOD. GENeSYS-MOD does not have the ability to retrofit old hydropower plants to increase their capacity. This, with the combination of hydropower capital cost levels being very high, results in no expansion in hydropower capacity. There is a temporary solution in the model, where the availability factor of hydropower is increased every year. This increases the annual power production from Norwegian hydropower every year in order to simulate an increase in capacity due to retrofitting. Therefore the hydropower capacity in Figure 6.6 is artificially constant.



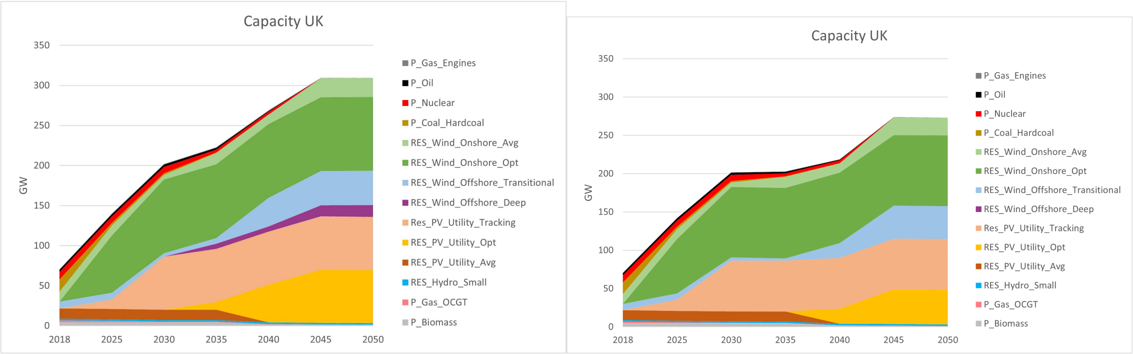
(a) Capacities in DK1 for run 1

(b) Capacities in DK1 run 2

Figure 6.7: Capacities in DK1 for run 1 and 2.

Figure 6.7a and 6.7b depict the capacities of DK1 without and with a connection to the offshore node, run 1 and run 2, respectively. Capacity expansion in DK1 for run 2 reaches its peak in 2030. This is when the model starts to build offshore wind in the offshore node, Run 2 in Figure 6.5. For run 1 the total installed capacity peaks at 43.8 GW in 2045. However, when connected to the offshore node the peak is only 23 GW in 2030. Offshore wind is the only technology with reduced capacity. The share is minimal in the energy mix for run 2, at only 5.7 GW in 2050. From the results of the Danish installed capacity, there is clearly a significant impact on the western Danish region. For further analysis, the power capacities of the UK will be studied in more detail.

Figure 6.8 depicts the capacities of the UK without and with a connection to the offshore node, run 2 and run3, respectively. The total capacity in 2045 for the



(a) Capacities in UK for run 2

(b) Capacities in UK run 3

Figure 6.8: Capacities in DK1 for run 2 and 3.

UK in run 2 is 314.9 GW. The majority of installed capacity comes from onshore wind and PV technologies. Offshore wind capacity holds both the transitional and deep technologies for offshore wind in 2050. The total expansion has a steady increase from 2018 to a peak in 2045. Nuclear, Oil, and Coal are phased out by 2045, which was specified in the input data. In run 3 the total capacity expansion halts between 2030 and 2040, before increasing to its peak at 279.3 GW in 2045, the majority of installed capacity is in onshore wind and PV technologies. The only present offshore wind technology, in this case, is transitional. While in run 2 deep offshore wind is also present.

From the results of the installed capacity, it is clear that the impact of an offshore node is greater in the Danish and the UK power system, compared to NO2. One reason for this is the energy mix of the countries. In 2050, the Norwegian bidding zone 2 has a small increase of 2.9% installed capacity from run 1 to run 2, However, DK1 sees a decrease of 60.2% in the same runs. The UK also experiences a decrease of 11.7% from run 2 to run 3. The reason for the disparity in growth is due to Norway's large capacity of hydropower. NO2 does not have to invest in new RES technology to meet its demand. Annual power production from hydropower plants in NO2 in 2050 is 221,98 PJ, while power demand is only 68,5 PJ. Neither DK1 nor UK has the potential for hydropower capacity and relies on installing RES technology to meet demand. This is only part of the reason, as there is still a question about why the UK and DK1 rely on the offshore node for capacity. There are a couple of reasons why this might be: preferable wind series or capital cost differences. If the wind series of the offshore node is less advantageous than that of DK1 or the UK, this might be an indication that the new capital costs for the offshore node are set too low. Relevant wind series are displayed below.

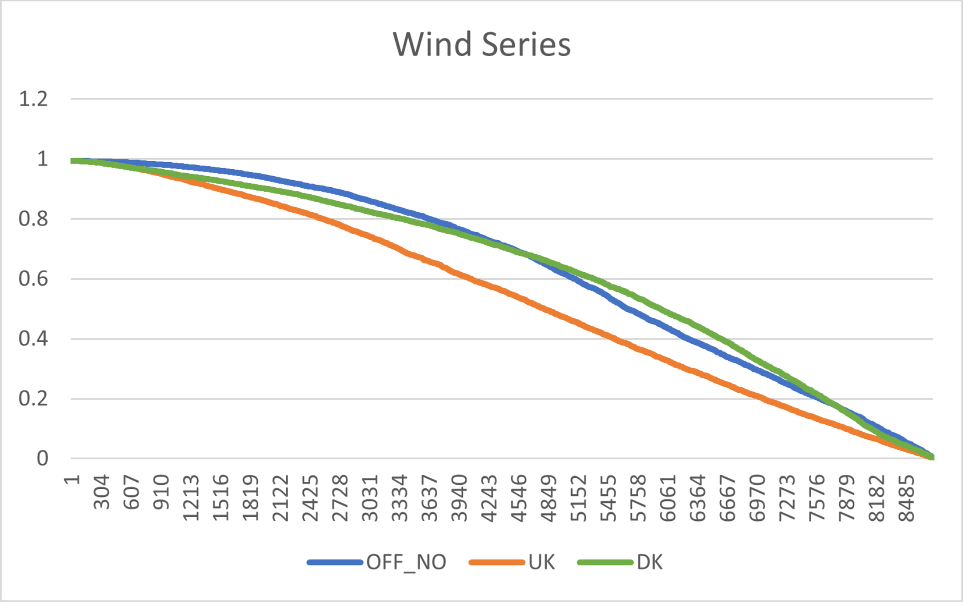


Figure 6.9: Windseries for OFF_NO, DK1 and UK

The series in figure 6.9 are sorted in descending order to easily display differences. It is apparent that the UK wind series has a lower average yield in comparison to the offshore node. The difference is so significant that this can justify why the model opts for utilizing the offshore node for capacity. The difference between Denmark and the offshore node is not as pronounced. However, from the results in Figure 6.7b, it is evident that almost all offshore wind is moved to the offshore node. This might indicate that either the new capital cost prices are too low or the old capital costs are too high. Further sensitivity analysis is required to test this. With the current values, the cost-optimal solution is to transfer offshore wind to the offshore node.

To verify the findings in this subsection, transmission capacity, power import, and power export are presented in the next sections.

6.2.2 Transmission Capacity

This section will present the transmission capacity between the offshore nodes and the connected regions. The purpose of looking into the transmission capacities is to get an idea of where the model wants to transport the power produced by the offshore node. It will also be utilized to draw connections to the installed capacities and power import and export later in the discussion.

Run 1		2018	2025	2030	2035	2040	2045	2050
OFF_NO	NO2	0	0	0	5.319	8.776	26.439	28.172

Run 2		2018	2025	2030	2035	2040	2045	2050
OFF_NO	NO2	0	0	0.075	3.646	7.431	9.191	9.191
OFF_NO	DK1	0	0	0.878	7.598	13.523	31.174	31.308

Run 3		2018	2025	2030	2035	2040	2045	2050
OFF_NO	NO2	0	0	0.335	4.036	7.819	7.819	8.713
OFF_NO	DK1	0	0	1.068	13.457	17.956	17.956	18.784
OFF_NO	UK	0	0	0.762	18.78	18.78	18.78	19.698

Table 6.3: Transmission capacity expansion for the offshore run.

Table 6.3 shows the transmission capacity expansions for every run. For run 1, capacity is built in 2035 and ends up at 28.2 GW in 2050. For run 2 the majority of transmission capacity is built to establish a connection to DK1 with 31.3 GW in 2050 and 9.2 GW to NO2. This is a total transmission capacity of 40.5 Gw in 2050. For run 3 the connection to Norway has a capacity of 8.7 GW, while DK1 and UK are quite similar at 18.8 GW and 19.7 GW respectively. The total transmission capacity for run 3 is 47.2. The total transmission capacity curve follows that of the installed capacity in the offshore node. The decreased capacities in DK1 and the UK are compensated with power production from the offshore node, the transmission capacities validate this. These results validate the claim that the offshore node substitutes for the installed capacities in DK1 and the UK.

6.2.3 Power Trade and Production

This section presents the power trade of the regions relevant to research question two, while power production in DK1 is shown to better understand the interplay between power production, import, and export. Germany is included in the power trade graphs because of its proximity and trade connections to both DK1 and DK2.

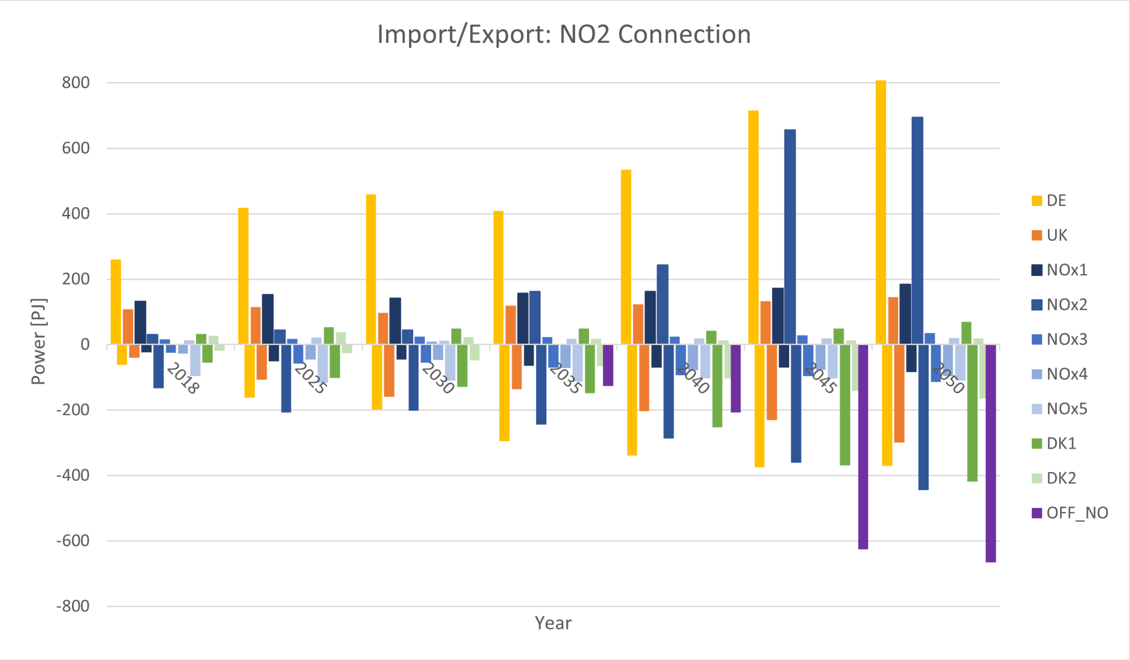


Figure 6.10: Import and Export of power for run 1

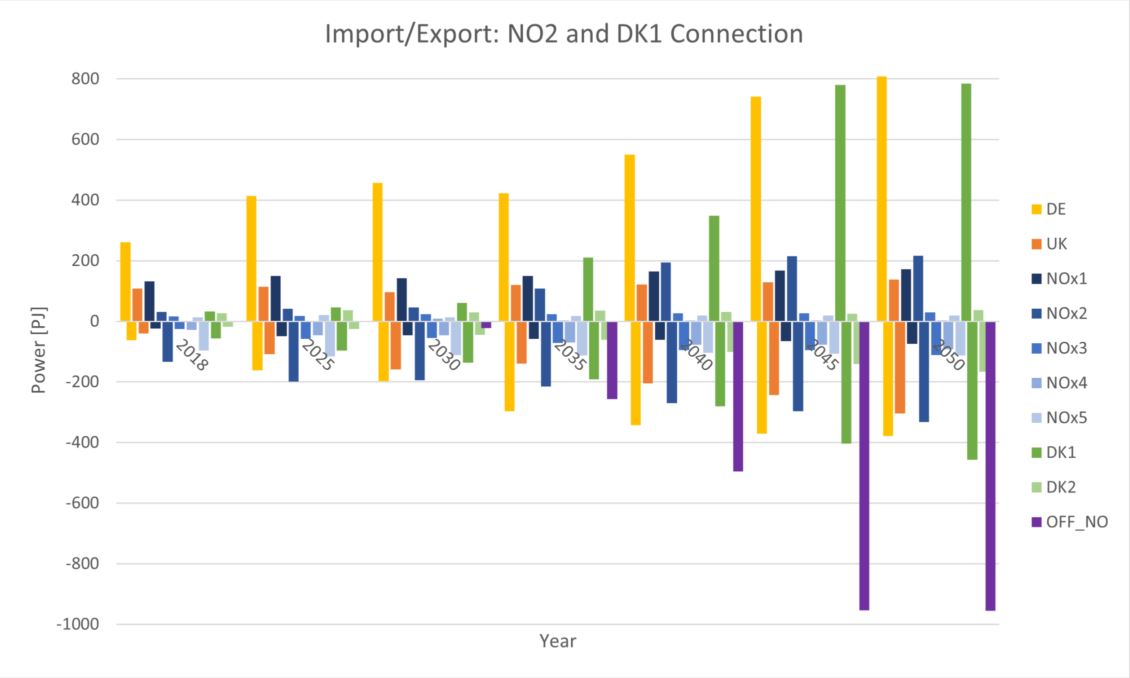


Figure 6.11: Import and Export of power for run 2

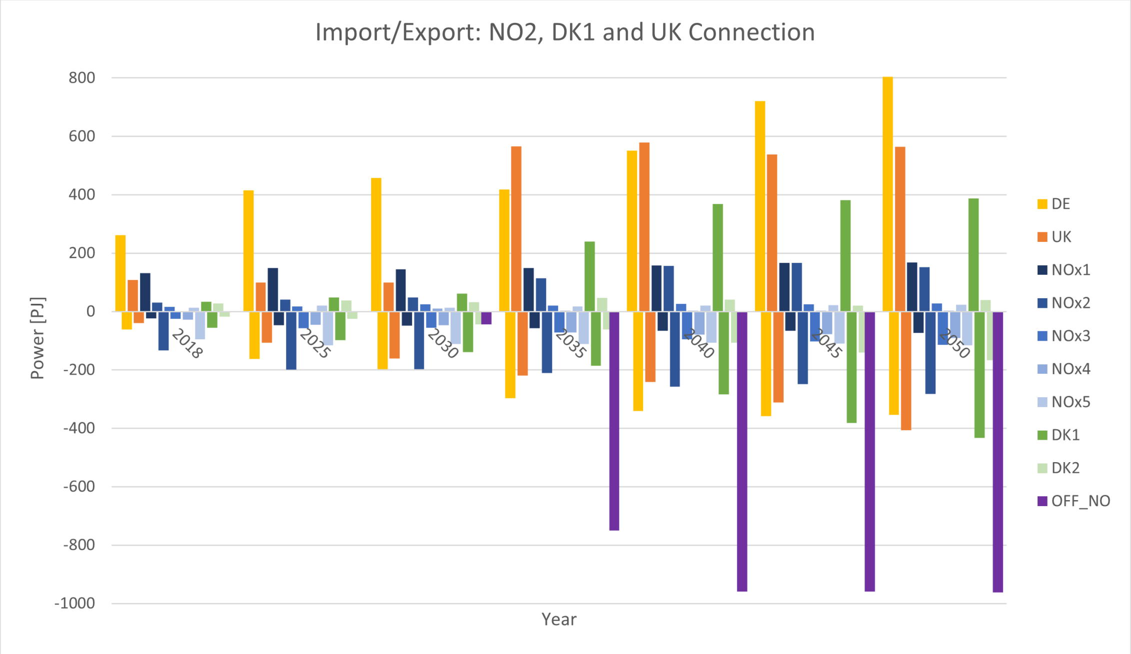
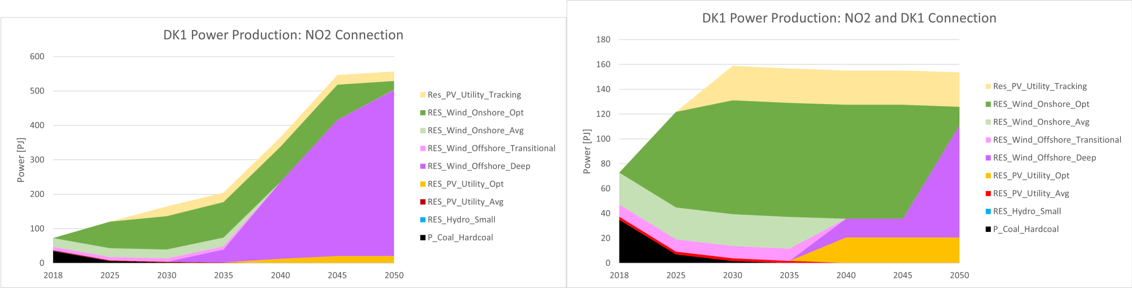


Figure 6.12: Import and Export of power for run 3

Figure 6.10, 6.11 and 6.12 represent the import as the positive columns and export as the negative columns for the three runs. In 6.10 NO2 has a large amount of power import at almost 694.2 PJ. NO2 has trade connections to the Netherlands, the UK, Germany, DK1, NO1, and NO5. The import for the other Norwegian nodes is relatively small. The offshore node exports about 666 PJ in 2050. In run 2, figure 6.11, DK1 import is almost at the level of the German power import in 2045 and 2050 at 784.3 PJ. The export for DK1 is 457.2 PJ. NO2 import is about 216.4 PJ. The offshore node exports 954.7 GW in both 2045 and 2050. UK Import is about 138.6 PJ. For run 3, Figure 6.12, UK import is about 563.9 PJ, NO2 import is 151.9 PJ, and DK1 import is 386.9 PJ. The export for the offshore node is 962.9 PJ in 2040, 2045, and 2050. In 2050, UK export is 406.4 PJ, NO2 export is 282.6 PJ, and DK1 export is 432.5 PJ.

Figure 6.4 and 6.13b show power production in the DK1 region for run 1 and run 2 respectively. Note, axis values differentiate in the two figures for legibility reasons**??**. In run 1, DK1 has an annual power production of 550 PJ. The vast majority of the power production is from offshore wind. For run 2 the power production reaches its peak in 2030 at 158 PJ.



(a) Power production in DK1 for run 1

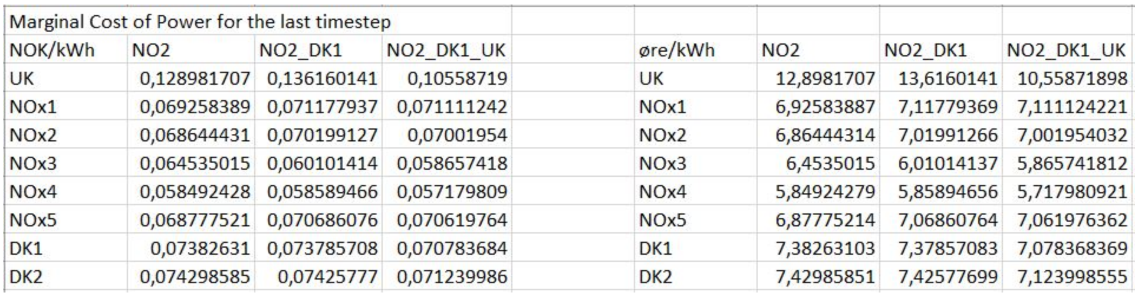
(b) Power production in DK1 for run 2

Figure 6.13: Power production in DK1 for run 1 and 2.

The import and export of power reflect the transmission capacities of the offshore node. With the power trade from the offshore node changing with the trade connections. However, the import does not change as much. For runs 1, 2, and 3 the import of DK1 changes from 69.6 PJ to 784.3 PJ and 386.9 PJ respectively. This is a vast increase by a factor of 11.3 in imports from run 1 to run 2 in 2050. While export stays almost constant. As import increases, power production decreases, as seen in figure 6.4 and 6.13b, the decrease is 72.4%. The power production reduction comes from a reduction in offshore wind power production. This is because the amount of offshore wind capacity in DK1 is reduced. An observation from the offshore node in both run 2 and run 3, is that export is constantly between 954.7 and 962.9 PJ in the years with 50 GW installed capacity. The fluctuation in export is due to assumptions of the model. The wind series in the model are historic and non-stochastic. The same is true for all time series data.

6.2.4 Marginal Cost

This section will present the marginal costs of power in the last time step in 2050 for DK1, UK, and NO1-5. It is important to note that no strong conclusions should be taken about the exact values. However, the purpose of the results is to investigate the marginal cost trends.



Marginal Cost of Power for the last timestep								
NOK/kWh	NO2	NO2_DK1	NO2_DK1_UK		øre/kWh	NO2	NO2_DK1	NO2_DK1_UK
UK	0,128981707	0,136160141	0,10558719		UK	12,8981707	13,6160141	10,55871898
NOx1	0,069258389	0,071177937	0,071111242		NOx1	6,92583887	7,11779369	7,111124221
NOx2	0,068644431	0,070199127	0,07001954		NOx2	6,86444314	7,01991266	7,001954032
NOx3	0,064535015	0,060101414	0,058657418		NOx3	6,4535015	6,01014137	5,865741812
NOx4	0,058492428	0,058589466	0,057179809		NOx4	5,84924279	5,85894656	5,717980921
NOx5	0,068777521	0,070686076	0,070619764		NOx5	6,87775214	7,06860764	7,061976362
DK1	0,07382631	0,073785708	0,070783684		DK1	7,38263103	7,37857083	7,078368369
DK2	0,074298585	0,07425777	0,071239986		DK2	7,42985851	7,42577699	7,123998555

Table 6.4: Marginal costs for the last timestep in 2050

Originally the costs were provided in MEUR/PJ so the following conversion was used:

$$1\frac{MEUR}{PJ} = \frac{1000000EUR}{277777MWh} = \frac{3.6 * 11.49NOK}{1000kWh} = 0.04136\frac{NOK}{kWh} \tag{6.1}$$

At the time of writing, the conversion rate from EUR to NOK is 11.49. The marginal costs range from 13,6 øre/kWh to 5,7 øre/kWh. The average cost is highest in the UK at 12,3 øre/kWh, Denmark and Norwegian costs are quite similar.

The main limitation of the model is the timestep choice of every 400th hour, this translates to 22 steps per year. RES technology is highly dependent on weather conditions, and the temporal resolution for these runs might not be sufficient for deep analysis. However, there is value in examining the trend of the cost. The highest marginal costs are in the UK, while NO4 has the lowest prices. The general trend for Norway is that NO4 has the lowest costs, then there is a small increase to NO3, followed by an increase to NO2, NO5, and NO1, which are all quite similar. This is interesting as this trend generally reflects the electricity costs in the Norwegian system [75]. The marginal costs in Denmark are higher, although the difference between DK1 and DK2 is minimal. There seems to be an indication that the grid configuration of the node does not have any major effect on the marginal costs in the connected regions. If anything the cost is the lowest when the offshore node is connected to all three regions.

Chapter 7

Conclusion

In this master thesis, the open source energy system model GENeSYS-MOD has been utilized to improve the dataset from openENTRANCE with a focus on offshore wind in the North Sea, and bordering regions. Offshore capacity has been removed from Norway and is modeled as a standalone node located at Sørlige Nordsjøen II. Denmark has also been disaggregated in order to better represent the Danish energy system. During the work, two research questions were developed.

Conclusion in regards to Research Question 1, the effect of disaggregating the Danish system. It can be concluded that it is important to disaggregate the region if it has a tendency to be affected by structural congestion. Countries that have these bottlenecks often opt for a zonal bidding electricity market, Italy, Sweden, Norway, and Denmark are examples of this, these regions should therefore be disaggregated to better represent power trade and capacity expansion. A bottleneck can happen when there is a high potential for RES in one region while demand is located elsewhere. Other regions that use one price area for their market, like the UK, might also benefit from the disaggregation. However, the biggest reason to disaggregate is problems connected to structural congestion. Countries like the UK mostly experience internal transient congestion due to short-term changes in power generation and/or demand [74] creating a mismatch between power generation and demand in a system. Disaggregation will then not yield as impactful results.

Conclusion in regards to Research Question 2, the effect of the increased interconnection of the offshore node. There is a clear trend with offshore wind in Sørlige nordsjøen II being more cost optimal if the node is interconnected in a meshed grid configuration compared to a radial grid. This finding is in contrast to the Norwegian government's current plans which opt for a radial solution [25]. The marginal cost of power in Norway is impacted minimally with a meshed grid compared to a radial grid connection. This is a very interesting find, however, no strong conclusion about the values of marginal cost or potential electricity prices should be drawn from the model before the model's fidelity is increased. In a meshed grid structure, most power is directly exported from the offshore node to Denmark and the UK

The model and dataset used in this master thesis are open source. This means that the improvements made during work for this Thesis can be utilized by other parties. The steps for implementing new offshore nodes or disaggregating existing regions are attached to the appendix of this Thesis. This provides a framework for further improvements to the open-source dataset.

7.1 Assumptions and limitations

Below is a short list of assumptions for the thesis:

- Offshore wind capital cost: The capital cost of offshore wind was adjusted to remove the grid connection costs portion of the preexisting capital cost. The adjustment was made based on a literature review of offshore wind energy costs. More specifically the values were based on a report from ICE [46]. The results indicate that the new costs might have been too low.

- Offshore wind farm location: It is assumed that all of the offshore wind capacity for Norway is located at Sørlige Nordsjøen II.

- Offshore wind upper bound: There has been set an upper bound for offshore wind in the offshore node at 50 GW. This limit is loosely based on Norwegian capacity expansion plans of 30 GW[2]. The limit was raised to 50 GW to provide the model with more freedom for cost optimization.

- Weather data: Currently the weather data in the DK1 and DK2 nodes is identical, this is an assumption made due to not finding the necessary weather data for the disaggregated nodes.

Below is a short list of limitations for the model:

- Transmission capacity: Transmission capacity for the offshore connected transmission lines is not correctly implemented in the model. When first adding offshore nodes to the model there was a problem connected to transmission expansion. In GENeSYS-MOD transmission capacity growth is based on a factor, this means that the model could not build transmission capacity when the transmission capacity was 0. An exception for the offshore node was therefore implemented. However, it seems like this removed the capacity growth limitations from the trade capacities connected to the offshore node. This is the reason the results showcase such drastic increases in transmission capacity.
- Hydropower: Hydropower lacks the option to retrofit old hydropower plants as a tool for capacity expansion. This has a temporary fix by increasing the availability factor for every sample year. This then ensures progressively higher hydropower power production, but the output capacity stays constant. Hydropower in the model also lacks stochastic inflow. These limitations play a large role in the Norwegian Energy system.
- Transmission capacity expansion costs: GENeSYS-MOD does not distinguish between different forms of transmission capacity. There is no choice of what type of line a connection is. So for the offshore connections, there is no choice whether to go for HVAC or HVDC solutions. This is important information for estimating costs, especially if in future work more offshore nodes will be added.

7.2 Future Work

Through the work with the low carbon scenario and the GENeSYS-MOD, several points have been identified for future improvements of the model and data.

- More offshore nodes should be added: In the current iteration of the model, all of the offshore wind in Norway is located in Sørlige Nordsjøen II. This is not a good representation of the Norwegian system as now the only Norwegian region connected to offshore wind is NO2. The new nodes should be based on plans for offshore wind farms. Offshore for the other regions in the model should also be moved to standalone nodes to make sure the model methodology is consistent. This will also open up opportunities for an in-depth analysis of offshore wind grid configurations.

- Streamlining: The framework created for adding offshore nodes is currently being done manually. This is unsatisfactory as this is not time effective and increases the probability of mistakes being introduced in the dataset. Although the current framework is relatively simple, see appendix 7.2, an automated script for the introduction of new offshore nodes should be developed.

- Time-series: Reducing the granularity of the time slices is essential to accurately represent the dynamics and variability of renewable energy sources, such as wind and solar. The methodology for the time-series reduction should therefore be revised as now the model struggle with lower timesteps. Another motivation for this is so that the model can run with emission limits at lower timesteps as well.

- Further disaggregation: To enhance the fidelity of the model in representing the Norwegian energy system, it is advisable to disaggregate additional countries. A priority should be given to the disaggregation of Sweden, considering the substantial electricity trading that takes place between Norway and different bidding zones in Sweden. Incorporating this disaggregation can capture the Norwegian intricacies of cross-border electricity flows more accurately.

- Weather data: Weather data for the disaggregated areas should be unique and geographically accurate. DK1 and DK2 have used the same hourly time series as DK from the original scenario since the new hourly series differentiated too much compared to the original. Right before the deadline the same code used to generate all hourly time series for the openENTRANCE project was acquired. This should be used to generate new time series for DK1, DK2, and other disaggregated areas. An alternative could be to incorporate weather data from other open-source data. ENTSO-E has public weather data available in connection to their Ten-Year Network Development Plan, this could be interesting to compare and maybe utilize.
- Transmission capacity limits: Limits for transmission capacity growth should integrate for the new offshore nodes, this is to ensure plausible transmission capacity expansion in the model.
- Capital cost sensitivity analysis: Some of the results of the model indicate that the model's new capital costs for offshore wind might be on the lower side. Therefore a more extensive literature review should be conducted to perform a sensitivity analysis on offshore capital costs.
- Hydropower: The limitations connected to hydropower in GENeSYS-MOD should be addressed. This will result in a model that can yield better results for analysis in regard to hydropower dependent countries like Norway.

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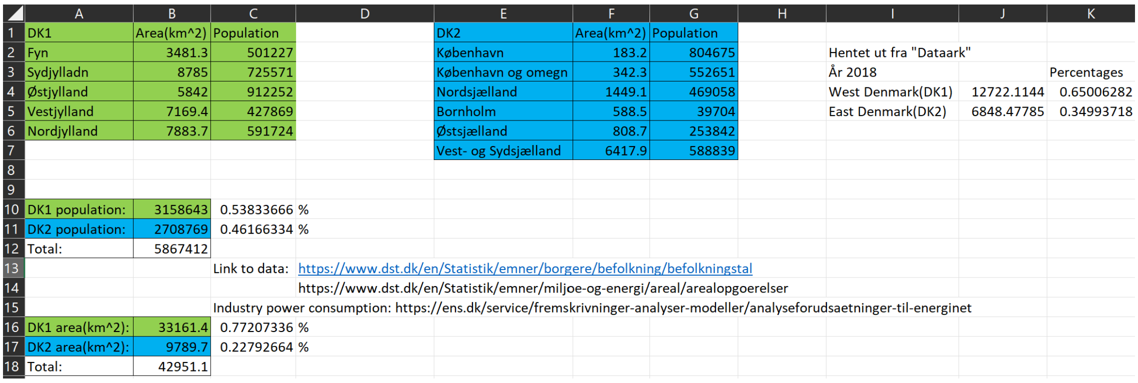
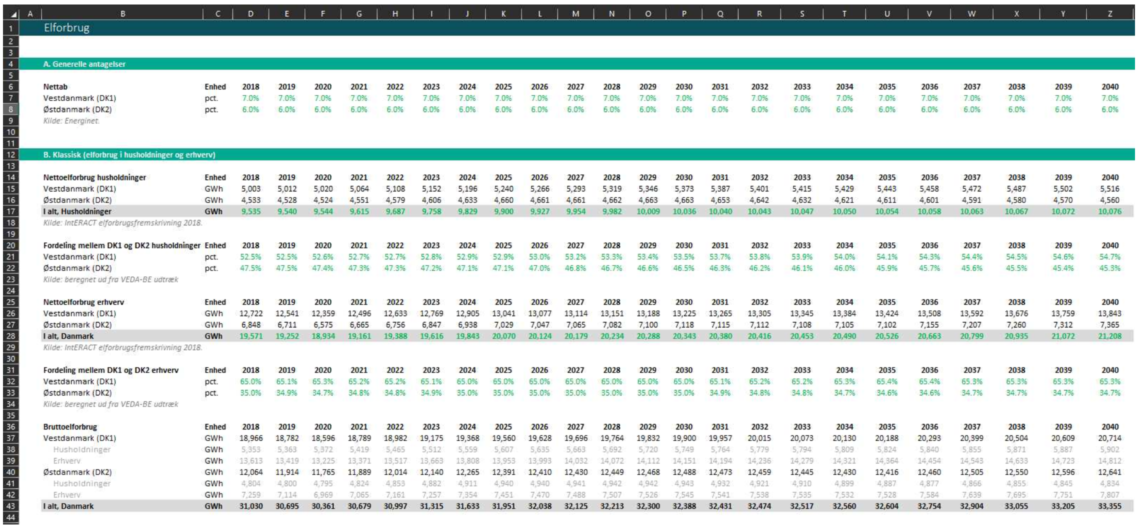
Appendix

Denmark data

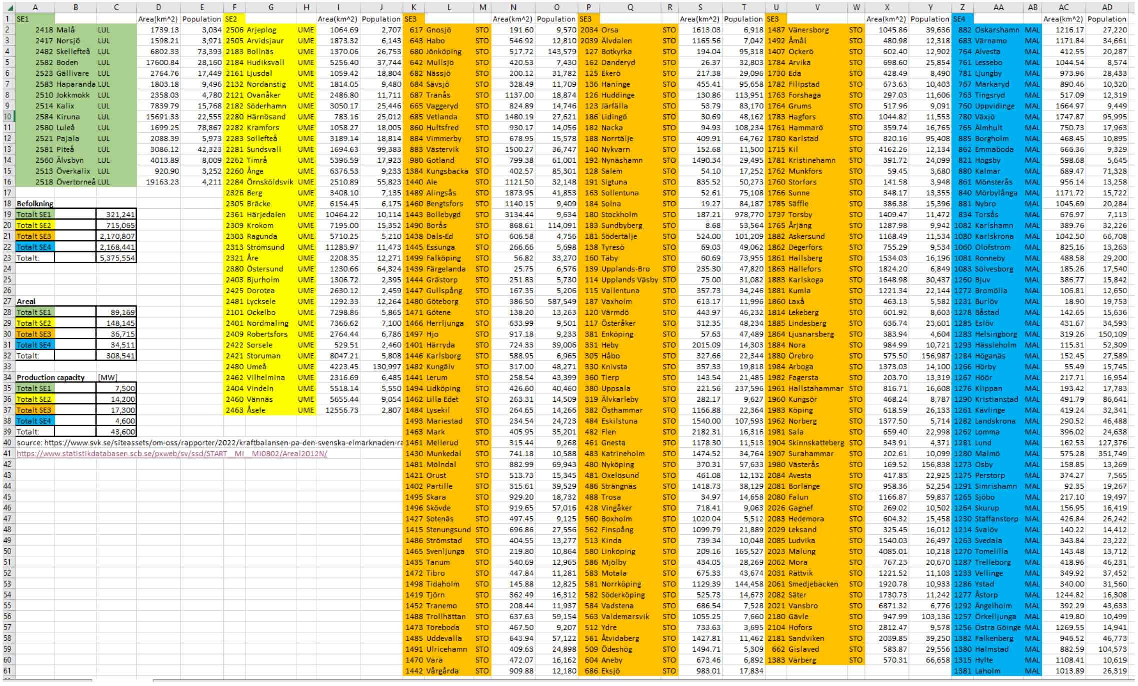


	A	B	C	D	E	F	G	H	I	J	K
1	DK1	Area(km^2)	Population		DK2	Area(km^2)	Population				
2	Fyn	3481.3	501227		København	183.2	804675		Hentet ut fra "Dataark"		
3	Sydjylladn	8785	725571		København og omegn	342.3	552651		År 2018		Percentages
4	Østjylland	5842	912252		Nordsjælland	1449.1	469058		West Denmark(DK1)	12722.1144	0.65006282
5	Vestjylland	7169.4	427869		Bornholm	588.5	39704		East Denmark(DK2)	6848.47785	0.34993718
6	Nordjylland	7883.7	591724		Østsjælland	808.7	253842				
7					Vest- og Sydsjælland	6417.9	588839				
8											
9											
10	DK1 population:	3158643	0.53833666 %								
11	DK2 population:	2708769	0.46166334 %								
12	Total:	5867412									
13			Link to data:	https://www.dst.dk/en/Statistik/emner/borgere/befolkning/befolkningstal							
14				https://www.dst.dk/en/Statistik/emner/miljoe-og-energi/areal/arealopgoerelser							
15			Industry power consumption: https://ens.dk/service/fremskrivninger-analyser-modeller/analyseforudsaetninger-til-energinet								
16	DK1 area(km^2):	33161.4	0.77207336 %								
17	DK2 area(km^2):	9789.7	0.22792664 %								
18	Total:	42951.1									

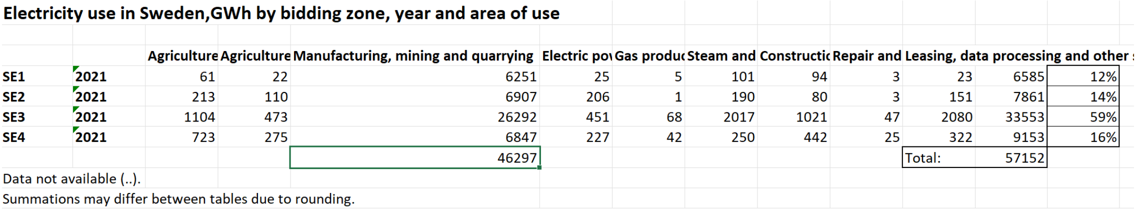


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1		Elforbrug																								
2																										
3																										
4		A. Generelle antagelser																								
5																										
6		Nettab	Enhed	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
7		Vestdanmark (DK1)	pct.	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
8		Østdanmark (DK2)	pct.	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
9		Kilde: Energinet.																								
10																										
11																										
12		B. Klassisk (elforbrug i husholdninger og erhverv)																								
13																										
14		Nettoelforbrug husholdninger	Enhed	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
15		Vestdanmark (DK1)	GWh	5,003	5,012	5,020	5,064	5,108	5,152	5,196	5,240	5,266	5,293	5,319	5,346	5,373	5,387	5,401	5,415	5,429	5,443	5,458	5,472	5,487	5,502	5,516
16		Østdanmark (DK2)	GWh	4,533	4,528	4,524	4,551	4,579	4,606	4,633	4,660	4,661	4,661	4,662	4,663	4,663	4,653	4,642	4,632	4,621	4,611	4,601	4,591	4,580	4,570	4,560
17		I alt, Husholdninger	GWh	9,535	9,540	9,544	9,615	9,687	9,758	9,829	9,900	9,927	9,954	9,982	10,009	10,036	10,040	10,043	10,047	10,050	10,054	10,058	10,063	10,067	10,072	10,076
18		Kilde: IntERACT elforbrugsfremskrivning 2018.																								
19																										
20		Fordeling mellem DK1 og DK2 husholdninger	Enhed	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
21		Vestdanmark (DK1)	pct.	52.5%	52.5%	52.6%	52.7%	52.7%	52.8%	52.9%	52.9%	53.0%	53.2%	53.3%	53.4%	53.5%	53.7%	53.8%	53.9%	54.0%	54.1%	54.3%	54.4%	54.5%	54.6%	54.7%
22		Østdanmark (DK2)	pct.	47.5%	47.5%	47.4%	47.3%	47.3%	47.2%	47.1%	47.1%	47.0%	46.8%	46.7%	46.6%	46.5%	46.3%	46.2%	46.1%	46.0%	45.9%	45.7%	45.6%	45.5%	45.4%	45.3%
23		Kilde: beregnet ud fra VEDA-BE udtræk																								
24																										
25		Nettoelforbrug erhverv	Enhed	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
26		Vestdanmark (DK1)	GWh	12,722	12,541	12,359	12,496	12,633	12,769	12,905	13,041	13,077	13,114	13,151	13,188	13,225	13,265	13,305	13,345	13,384	13,424	13,508	13,592	13,676	13,759	13,843
27		Østdanmark (DK2)	GWh	6,848	6,711	6,575	6,665	6,756	6,847	6,938	7,029	7,047	7,065	7,082	7,100	7,118	7,115	7,112	7,108	7,105	7,102	7,155	7,207	7,260	7,312	7,365
28		I alt, Danmark	GWh	19,571	19,252	18,934	19,161	19,388	19,616	19,843	20,070	20,124	20,179	20,234	20,288	20,343	20,380	20,416	20,453	20,490	20,526	20,663	20,799	20,935	21,072	21,208
29		Kilde: IntERACT elforbrugsfremskrivning 2018.																								
30																										
31		Fordeling mellem DK1 og DK2 erhverv	Enhed	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
32		Vestdanmark (DK1)	pct.	65.0%	65.1%	65.3%	65.2%	65.2%	65.1%	65.0%	65.0%	65.0%	65.0%	65.0%	65.0%	65.0%	65.1%	65.2%	65.2%	65.3%	65.4%	65.4%	65.3%	65.3%	65.3%	65.3%
33		Østdanmark (DK2)	pct.	35.0%	34.9%	34.7%	34.8%	34.8%	34.9%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	35.0%	34.9%	34.8%	34.8%	34.7%	34.6%	34.6%	34.7%	34.7%	34.7%	34.7%
34		Kilde: beregnet ud fra VEDA-BE udtræk																								
35																										
36		Bruttoelforbrug	Enhed	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
37		Vestdanmark (DK1)	GWh	18,966	18,782	18,596	18,789	18,982	19,175	19,368	19,560	19,628	19,696	19,764	19,832	19,900	19,957	20,015	20,073	20,130	20,188	20,293	20,399	20,504	20,609	20,714
38		Husholdninger	GWh	5,353	5,363	5,372	5,419	5,465	5,512	5,559	5,607	5,635	5,663	5,692	5,720	5,749	5,764	5,779	5,794	5,809	5,824	5,840	5,855	5,871	5,887	5,902
39		Erhverv	GWh	13,613	13,419	13,225	13,371	13,517	13,663	13,808	13,953	13,993	14,032	14,072	14,112	14,151	14,194	14,236	14,279	14,321	14,364	14,454	14,543	14,633	14,723	14,812
40		Østdanmark (DK2)	GWh	12,064	11,914	11,765	11,889	12,014	12,140	12,265	12,391	12,410	12,430	12,449	12,468	12,488	12,473	12,459	12,445	12,430	12,416	12,460	12,505	12,550	12,596	12,641
41		Husholdninger	GWh	4,804	4,800	4,795	4,824	4,853	4,882	4,911	4,940	4,940	4,941	4,942	4,942	4,943	4,932	4,921	4,910	4,899	4,887	4,877	4,866	4,855	4,845	4,834
42		Erhverv	GWh	7,259	7,114	6,969	7,065	7,161	7,257	7,354	7,451	7,470	7,488	7,507	7,526	7,545	7,541	7,538	7,535	7,532	7,528	7,584	7,639	7,695	7,751	7,807
43		I alt, Danmark	GWh	31,030	30,695	30,361	30,679	30,997	31,315	31,633	31,951	32,038	32,125	32,213	32,300	32,388	32,431	32,474	32,517	32,560	32,604	32,754	32,904	33,055	33,205	33,355
44																										

Sweden data



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1	SE1			Area(km^2)	Population	SE2			Area(km^2)	Population	SE3			Area(km^2)	Population	SE3			Area(km^2)	Population	SE3			Area(km^2)	Population	SE4			Area(km^2)	Population
2	2418	Malå	LUL	1739.13	3,034	2506	Arjeplog	UME	1064.69	2,707	617	Gnosjö	STO	191.60	9,570	2034	Orsa	STO	1613.03	6,918	1487	Vänersborg	STO	1045.86	39,636	882	Oskarshamn	MAL	1216.17	27,220
3	2417	Norsjö	LUL	1598.21	3,971	2505	Arvidsjaur	UME	1873.32	6,143	643	Habo	STO	546.92	12,810	2039	Älvdalen	STO	1165.56	7,042	1492	Åmål	STO	480.98	12,318	683	Värnamo	MAL	1171.84	34,661
4	2482	Skellefteå	LUL	6802.33	73,393	2183	Bollnäs	UME	1370.06	26,753	680	Jönköping	STO	517.72	143,579	127	Botkyrka	STO	194.04	95,318	1407	Öckerö	STO	602.40	12,902	764	Alvesta	MAL	412.55	20,287
5	2582	Boden	LUL	17600.84	28,160	2184	Hudiksvall	UME	5256.40	37,744	642	Mullsjö	STO	420.53	7,430	162	Danderyd	STO	26.37	32,803	1784	Arvika	STO	698.60	25,854	761	Lessebo	MAL	1044.54	8,574
6	2523	Gällivare	LUL	2764.76	17,449	2161	Ljusdal	UME	1059.42	18,804	682	Nässjö	STO	200.12	31,782	125	Ekerö	STO	217.38	29,096	1730	Eda	STO	428.49	8,490	781	Ljungby	MAL	973.96	28,433
7	2583	Haparanda	LUL	1803.18	9,496	2132	Nordanstig	UME	1814.05	9,480	684	Sävsjö	STO	328.49	11,709	136	Haninge	STO	455.41	95,658	1782	Filipstad	STO	673.63	10,403	767	Markaryd	MAL	890.46	10,320
8	2510	Jokkmokk	LUL	2358.03	4,780	2121	Ovanåker	UME	2486.80	11,711	687	Tranås	STO	1137.00	18,874	126	Huddinge	STO	130.86	113,951	1763	Forshaga	STO	297.03	11,606	763	Tingsryd	MAL	517.09	12,319
9	2514	Kalix	LUL	7839.79	15,768	2182	Söderhamn	UME	3050.17	25,446	665	Vaggeryd	STO	824.89	14,746	123	Järfälla	STO	53.79	83,170	1764	Grums	STO	517.96	9,091	760	Uppvidinge	MAL	1664.97	9,449
10	2584	Kiruna	LUL	15691.33	22,555	2280	Härnösand	UME	783.16	25,012	685	Vetlanda	STO	1480.19	27,621	186	Lidingö	STO	30.69	48,162	1783	Hagfors	STO	1044.82	11,553	780	Växjö	MAL	1747.87	95,995
11	2580	Luleå	LUL	1699.25	78,867	2282	Kramfors	UME	1058.27	18,005	860	Hultsfred	STO	930.17	14,056	182	Nacka	STO	94.93	108,234	1761	Hammarö	STO	359.74	16,765	765	Älmhult	MAL	750.73	17,963
12	2521	Pajala	LUL	2088.39	5,973	2283	Sollefteå	UME	3189.14	18,814	884	Vimmerby	STO	678.95	15,578	188	Norrtälje	STO	409.91	64,762	1780	Karlstad	STO	820.16	95,408	885	Borgholm	MAL	468.45	10,895
13	2581	Piteå	LUL	3086.12	42,323	2281	Sundsvall	UME	1694.63	99,383	883	Västervik	STO	1500.27	36,747	140	Nykvarn	STO	152.68	11,500	1715	Kil	STO	4162.26	12,134	862	Emmaboda	MAL	666.36	9,329
14	2560	Älvsbyn	LUL	4013.89	8,009	2262	Timrå	UME	5396.59	17,923	980	Gotland	STO	799.38	61,001	192	Nynäshamn	STO	1490.34	29,495	1781	Kristinehamn	STO	391.72	24,099	821	Högsby	MAL	598.68	5,645
15	2513	Överkalix	LUL	920.90	3,252	2260	Ånge	UME	6376.53	9,233	1384	Kungsbacka	STO	402.57	85,301	128	Salem	STO	54.10	17,252	1762	Munkfors	STO	59.45	3,680	880	Kalmar	MAL	689.47	71,328
16	2518	Övertorneå	LUL	19163.23	4,211	2284	Örnsköldsvik	UME	2510.89	55,823	1440	Ale	STO	1121.50	32,148	191	Sigtuna	STO	835.52	50,273	1760	Storfors	STO	141.58	3,948	861	Mönsterås	MAL	956.14	13,258
17						2326	Berg	UME	3408.10	7,135	1489	Alingsås	STO	1873.95	41,853	163	Sollentuna	STO	52.61	75,108	1766	Sunne	STO	348.17	13,355	840	Mörbylånga	MAL	1171.72	15,722
18	**Befolkning**					2305	Bräcke	UME	6154.45	6,175	1460	Bengtsfors	STO	1140.15	9,409	184	Solna	STO	19.27	84,187	1785	Säffle	STO	386.38	15,396	881	Nybro	MAL	1045.69	20,284
19	Totalt SE1		321,241			2361	Härjedalen	UME	10464.22	10,114	1443	Bollebygd	STO	3134.44	9,634	180	Stockholm	STO	187.21	978,770	1737	Torsby	STO	1409.47	11,472	834	Torsås	MAL	676.97	7,113
20	Totalt SE2		715,065			2309	Krokom	UME	7195.00	15,352	1490	Borås	STO	868.61	114,091	183	Sundbyberg	STO	8.68	53,564	1765	Årjäng	STO	1287.98	9,942	1082	Karlshamn	MAL	389.76	32,226
21	Totalt SE3		2,170,807			2303	Ragunda	UME	5710.25	5,210	1438	Dals-Ed	STO	606.58	4,756	181	Södertälje	STO	524.00	101,209	1882	Askersund	STO	1168.49	11,534	1080	Karlskrona	MAL	1042.50	66,708
22	Totalt SE4		2,168,441			2313	Strömsund	UME	11283.97	11,473	1445	Essunga	STO	266.66	5,698	138	Tyresö	STO	69.03	49,062	1862	Degerfors	STO	755.29	9,534	1060	Olofström	MAL	825.16	13,263
23	Totalt:		5,375,554			2321	Åre	UME	2208.35	12,271	1499	Falköping	STO	56.82	33,270	160	Täby	STO	60.69	73,955	1861	Hallsberg	STO	1534.03	16,196	1081	Ronneby	MAL	488.58	29,200
24						2380	Östersund	UME	1230.66	64,324	1439	Färgelanda	STO	25.75	6,576	139	Upplands-Bro	STO	235.30	47,820	1863	Hällefors	STO	1824.20	6,849	1083	Sölvesborg	MAL	185.26	17,540
25						2403	Bjurholm	UME	1306.72	2,395	1444	Grästorp	STO	251.83	5,730	114	Upplands Väsby	STO	75.00	31,082	1883	Karlskoga	STO	1648.98	30,437	1260	Bjuv	MAL	386.77	15,842
26						2425	Dorotea	UME	2630.12	2,459	1447	Gullspång	STO	167.35	5,206	115	Vallentuna	STO	357.73	34,246	1881	Kumla	STO	1221.34	22,144	1272	Bromölla	MAL	106.81	12,650
27	**Areal**					2481	Lycksele	UME	1292.33	12,264	1480	Göteborg	STO	386.50	587,549	187	Vaxholm	STO	613.17	11,996	1860	Laxå	STO	463.13	5,582	1231	Burlöv	MAL	18.90	19,753
28	Totalt SE1		89,169			2101	Ockelbo	UME	7298.86	5,865	1471	Götene	STO	138.20	13,263	120	Värmdö	STO	443.97	46,232	1814	Lekeberg	STO	601.92	8,603	1278	Båstad	MAL	142.65	15,636
29	Totalt SE2		148,145			2401	Nordmaling	UME	7366.62	7,100	1466	Herrljunga	STO	633.99	9,501	117	Österåker	STO	312.35	48,234	1885	Lindesberg	STO	636.74	23,601	1285	Eslöv	MAL	431.67	34,593
30	Totalt SE3		36,715			2409	Robertsfors	UME	2764.44	6,786	1497	Hjo	STO	917.18	9,233	381	Enköping	STO	57.63	47,489	1864	Ljusnarsberg	STO	383.94	4,604	1283	Helsingborg	MAL	319.26	150,109
31	Totalt SE4		34,511			2422	Sorsele	UME	529.51	2,460	1401	Härryda	STO	724.33	39,006	331	Heby	STO	2015.09	14,303	1884	Nora	STO	984.99	10,721	1293	Hässleholm	MAL	115.31	52,309
32	Totalt:		308,541			2421	Storuman	UME	8047.21	5,808	1446	Karlsborg	STO	588.95	6,965	305	Håbo	STO	327.66	22,344	1880	Örebro	STO	575.50	156,987	1284	Höganäs	MAL	152.45	27,589
33						2480	Umeå	UME	4223.45	130,997	1482	Kungälv	STO	317.00	48,271	330	Knivsta	STO	357.33	19,818	1984	Arboga	STO	1373.03	14,100	1266	Hörby	MAL	55.49	15,745
34	**Production capacity**		[MW]			2462	Vilhelmina	UME	2316.69	6,485	1441	Lerum	STO	258.54	43,399	360	Tierp	STO	143.54	21,485	1982	Fagersta	STO	203.70	13,319	1267	Höör	MAL	217.71	16,954
35	Totalt SE1		7,500			2404	Vindeln	UME	5518.14	5,550	1494	Lidköping	STO	426.60	40,460	380	Uppsala	STO	221.56	237,596	1961	Hallstahammar	STO	816.71	16,608	1276	Klippan	MAL	193.42	17,783
36	Totalt SE2		14,200			2460	Vännäs	UME	5655.44	9,054	1462	Lilla Edet	STO	263.31	14,509	319	Älvkarleby	STO	282.17	9,627	1960	Kungsör	STO	468.24	8,787	1290	Kristianstad	MAL	491.79	86,641
37	Totalt SE3		17,300			2463	Åsele	UME	12556.73	2,807	1484	Lysekil	STO	264.65	14,266	382	Östhammar	STO	1166.88	22,364	1983	Köping	STO	618.59	26,133	1261	Kävlinge	MAL	419.24	32,341
38	Totalt SE4		4,600								1493	Mariestad	STO	234.54	24,723	484	Eskilstuna	STO	1540.00	107,593	1962	Norberg	STO	1377.50	5,714	1282	Landskrona	MAL	290.52	46,488
39	Totalt:		43,600								1463	Mark	STO	405.95	35,201	482	Flen	STO	2182.31	16,316	1981	Sala	STO	659.40	22,998	1262	Lomma	MAL	396.02	24,638
40	source: https://www.svk.se/siteassets/om-oss/rapporter/2022/kraftbalansen-pa-den-svenska-elmarknaden-ra										1461	Mellerud	STO	315.44	9,268	461	Gnesta	STO	1178.30	11,513	1904	Skinnskatteberg	STO	343.91	4,371	1281	Lund	MAL	162.53	127,376
41	https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__MI__MI0802/Areal2012N/										1430	Munkedal	STO	741.18	10,588	483	Katrineholm	STO	1474.52	34,764	1907	Surahammar	STO	202.61	10,099	1280	Malmö	MAL	575.28	351,749
42											1481	Mölndal	STO	882.99	69,943	480	Nyköping	STO	370.31	57,633	1980	Västerås	STO	169.52	156,838	1273	Osby	MAL	158.85	13,269
43											1421	Orust	STO	513.73	15,345	481	Oxelösund	STO	461.08	12,132	2084	Avesta	STO	417.83	22,925	1275	Perstorp	MAL	374.27	7,565
44											1402	Partille	STO	315.61	39,529	486	Strängnäs	STO	1418.73	38,129	2081	Borlänge	STO	958.36	52,254	1291	Simrishamn	MAL	92.35	19,267
45											1495	Skara	STO	929.20	18,732	488	Trosa	STO	34.97	14,658	2080	Falun	STO	1166.87	59,837	1265	Sjöbo	MAL	217.10	19,497
46											1496	Skövde	STO	919.65	57,016	428	Vingåker	STO	718.41	9,063	2026	Gagnef	STO	269.02	10,502	1264	Skurup	MAL	156.95	16,419
47											1427	Sotenäs	STO	497.45	9,125	560	Boxholm	STO	1020.04	5,512	2083	Hedemora	STO	604.32	15,458	1230	Staffanstorp	MAL	426.84	26,242
48											1415	Stenungsund	STO	696.86	27,556	562	Finspång	STO	1099.79	21,889	2029	Leksand	STO	325.45	16,012	1214	Svalöv	MAL	140.22	14,412
49											1486	Strömstad	STO	404.55	13,277	513	Kinda	STO	739.34	10,048	2085	Ludvika	STO	1540.03	26,497	1263	Svedala	MAL	343.84	23,222
50											1465	Svenljunga	STO	219.80	10,864	580	Linköping	STO	209.16	165,527	2023	Malung	STO	4085.01	10,218	1270	Tomelilla	MAL	143.48	13,712
51											1435	Tanum	STO	540.69	12,965	586	Mjölby	STO	434.05	28,269	2062	Mora	STO	767.23	20,670	1287	Trelleborg	MAL	418.96	46,231
52											1472	Tibro	STO	447.84	11,281	583	Motala	STO	675.33	43,674	2031	Rättvik	STO	1221.52	11,103	1233	Vellinge	MAL	349.92	37,452
53											1498	Tidaholm	STO	145.88	12,825	581	Norrköping	STO	1129.39	144,458	2061	Smedjebacken	STO	1920.78	10,933	1286	Ystad	MAL	340.00	31,560
54											1419	Tjörn	STO	362.49	16,312	582	Söderköping	STO	525.73	14,673	2082	Säter	STO	1730.73	11,242	1277	Åstorp	MAL	1244.82	16,308
55											1452	Tranemo	STO	208.44	11,937	584	Vadstena	STO	686.54	7,528	2021	Vansbro	STO	6871.32	6,776	1292	Ängelholm	MAL	392.29	43,633
56											1488	Trollhättan	STO	637.63	59,154	563	Valdemarsvik	STO	1055.25	7,660	2180	Gävle	STO	947.99	103,136	1257	Örkelljunga	MAL	419.80	10,499
57											1473	Töreboda	STO	467.50	9,207	512	Ydre	STO	733.63	3,695	2104	Hofors	STO	2812.47	9,578	1256	Östra Göinge	MAL	1269.55	14,941
58											1485	Uddevalla	STO	643.94	57,122	561	Åtvidaberg	STO	1427.81	11,462	2181	Sandviken	STO	2039.85	39,250	1382	Falkenberg	MAL	946.52	46,773
59											1491	Ulricehamn	STO	409.63	24,898	509	Ödeshög	STO	1494.71	5,309	662	Gislaved	STO	583.87	29,556	1380	Halmstad	MAL	882.59	104,573
60											1470	Vara	STO	472.07	16,162	604	Aneby	STO	673.46	6,892	1383	Varberg	STO	570.31	66,658	1315	Hylte	MAL	1108.41	10,619
61											1442	Vårgårda	STO	909.88	12,180	686	Eksjö	STO	983.01	17,834						1381	Laholm	MAL	1013.89	26,319



Electricity use in Sweden,GWh by bidding zone, year and area of use

		Agriculture	Agriculture	Manufacturing, mining and quarrying	Electric po	Gas produc	Steam and	Constructic	Repair and	Leasing, data processing and other		
SE1	**2021**	61	22	6251	25	5	101	94	3	23	6585	12%
SE2	**2021**	213	110	6907	206	1	190	80	3	151	7861	14%
SE3	**2021**	1104	473	26292	451	68	2017	1021	47	2080	33553	59%
SE4	**2021**	723	275	6847	227	42	250	442	25	322	9153	16%
				46297						Total:	57152	

Data not available (..).

Summations may differ between tables due to rounding.

Carbon emission limits

Region	Emission	1990	2018	2020	2025	2030	2035	2040	2045	2050
AT	CO2	67	999999	999999	999999	21.44	16.08	10.72	5.36	0
BE	CO2	146	999999	999999	999999	46.72	35.04	23.36	11.68	0
CH	CO2	55	999999	999999	999999	17.6	13.2	8.8	4.4	0
CZ	CO2	191	999999	999999	999999	61.12	45.84	30.56	15.28	0
DE	CO2	1280	999999	999999	999999	409.6	307.2	204.8	102.4	0
DK	CO2	80	999999	999999	999999	25.6	19.2	12.8	6.4	0
EE	CO2	37	999999	999999	999999	11.84	8.88	5.92	2.96	0
ES	CO2	258	999999	999999	999999	82.56	61.92	41.28	20.64	0
FI	CO2	58	999999	999999	999999	18.56	13.92	9.28	4.64	0
FR	CO2	529	999999	999999	999999	169.28	126.96	84.64	42.32	0
IE	CO2	62	999999	999999	999999	19.84	14.88	9.92	4.96	0
LT	CO2	43	999999	999999	999999	13.76	10.32	6.88	3.44	0
LU	CO2	13.5	999999	999999	999999	4.32	3.24	2.16	1.08	0
LV	CO2	14	999999	999999	999999	4.48	3.36	2.24	1.12	0
NL	CO2	231	999999	999999	999999	73.92	55.44	36.96	18.48	0
NO	CO2	41.5	999999	999999	999999	13.28	9.96	6.64	3.32	0
PL	CO2	446	999999	999999	999999	142.72	107.04	71.36	35.68	0
SE	CO2	68	999999	999999	999999	21.76	16.32	10.88	5.44	0
UK	CO2	822	999999	999999	999999	263.04	197.28	131.52	65.76	0

Table 7.1: Emission levels (in million tonnes) for different regions

Conference paper

Large-scale Offshore Wind Development and Decarbonization Pathways of the Norwegian Energy System

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***Abstract*—Modelling of the energy system in the countries surrounding the North Sea is performed with a focus on Norway and offshore wind farms situated in the North Sea. The geographically heterogeneous consumption and production distribution in Norway warrants a disaggregation of the country into separate regions. The ambitious targets set forth by the Norwegian government to license 30 GW of offshore wind generation capacity by 2040 also make the detailed study of the effects of such a large introduction of intermittent renewable energy relevant. We have selected to adhere to the Norwegian power market price zones in our disaggregation, resulting in five regions in Norway. In addition, a separate offshore zone has been added for offshore wind energy generation. This paper studies the resulting optimal capacity expansion and energy dispatch from the energy system model GENeSYS-MOD as a result of a) the disaggregation of Norway into 5 regions b) the introduction of an offshore region for offshore wind generation connected to NO2. The modeled time frame is from 2018 to 2050. The results show that a large introduction of offshore wind capacity results in less capacity expansion of onshore wind and considerably less solar capacity development.**

***Index Terms*—Energy systems, Offshore wind, Norwegian energy system**

I. INTRODUCTION

The energy system is in rapid and unprecedented (in modern times) development. Urgent actions are needed both from a sustainability and an energy security perspective. One of the most promising new developments is the large growth of offshore wind energy in Europe and the North Sea. The European Union (EU) set an ambitious plan for introducing 300 GW offshore wind production capacity in Europe [1]. The Norwegian government has also put forward a large-scale investment plan for offshore wind. The ambition is to allocate licensing areas for 30 GW of offshore wind production capacity within 2040 on the Norwegian continental shelf [2]. Offshore wind appears to be the dominating new source of power production in the future Norwegian energy mix due to the opposition to onshore wind power development and limited potential for production expansion in hydropower and solar power production. However, this plan poses a need to investigate the interaction between energy sectors (power, gas, and heat) on national and regional levels and prepare necessary development in the Norwegian energy sectors.

The favourable characteristics of hydropower in general, and the highly storable Norwegian hydropower specifically, make this technology a good candidate for facilitating the integration of variable renewable energy sources in the power system. The advantages of large-scale offshore wind integration into the Nordic electricity system and support from the hydropower-dominated Norwegian system have been studied previously [3]–[5]. However, there is still a need to investigate the impact of such integration on the overall Norwegian energy system.

Energy system modelling with low-carbon scenarios is necessary to analyse possible energy system developments toward reaching global climate goals. Energy system modelling is a crucial tool to give insights into decarbonization pathways and the impacts of climate change. Several models exist to analyze energy systems, e.g., MESSAGE [6], PRIMES [7], EFOM [8] and POLES [9]. The Integrated Markal Efom System (TIMES) is a bottom-up, techno-economic model generator for local, national, or multi-regional energy systems [10]. TIMES is the successor of the MARKet ALlocation model (MARKAL) and gives a detailed description of the entire energy system, including all resources, energy production technologies, energy carriers, demand devices, and sector demand for energy services. TIMES-Norway was developed in cooperation between the Norwegian Water Resources and Energy Directorate (NVE) and the Institute of Energy Technology (IFE). The model has been used extensively to analyse the long-term Norwegian energy system. TIMES-Norway has been applied to investigate possible ways for Norway to reach its target for 2020 [11], [12]. Many long-established models in the energy research community are not open-sourced, and the data sets are not openly available. Therefore, the open-data, open-source, long-term energy system model GENeSYS-MOD developed by Technical University Berlin is selected to model the low-carbon scenarios [13]. The high level of sector detail makes

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GENeSYS-MOD suitable for modelling global and regional decarbonization scenarios. This article provides insight into the impact of offshore wind integration on decarbonization scenarios for future developments of the Norwegian energy system. Norway has large regional differences regarding power generation and consumption. For instance, the region around the capital is more densely populated, and the electricity demand is high, whereas power production is low compared to other areas, such as the West and South-West regions, with ample hydropower resources. We disaggregate the Norwegian energy system into several regions to investigate the regional availability of the resources. Offshore wind is considered in a separate region. The energy system model can be used for identifying bottlenecks in the electricity grid and the need for new generation capacity and/or new transmission lines between regions [14]. To ensure model validity, available statistics and data are used to validate and make improvement suggestions for the Norwegian energy system.

II. METHODOLOGY

In our setup, GENeSYS-MOD endogenously determines dispatch and investment decisions for generation, storage, and transmission from 2018 to 2050 in five-year intervals [15]. The cost-minimizing objective function is formulated as a linear problem and defined as follows:

$$min\ cost = \sum_{r}\sum_{t}\sum_{y} TDC_{r,t,y} + \sum_{r}\sum_{y} TDTC_{r,y} \quad (1)$$

where *TDTC is Total Discounted Trading Cost* and *TDC is Total Discounted Cost* and calculated as:

$$\begin{aligned} TDC_{r,t,y} = DOC_{r,t,y} + DCI_{r,t,y} + DCIS_{r,t,y} \\ + DTEP_{r,t,y} - DSV_{r,t,y} \end{aligned}$$

The abbreviations from equation (1) are *Discounted Operating Cost (DOC)*, *Discounted Capital Investment (DCI)*, *Discounted Capital Investment Storage (DCIS)*, *Discounted Technology Emission Penalty (DTEP)*, and *Discounted Salvage Value (DSV)*. All the parameters are defined for each *year (y)*, *technology (t)*, and *region (r)* and discounted with 5%. A detailed model description is provided in [15].

The spatial modelling covers all Nordic (Norway, Sweden, Finland, and Denmark) and Baltic (Estonia, Latvia, and Lithuania) countries. In addition, central European countries (Germany, Poland, France, Belgium, the Netherlands, Spain, Switzerland, Luxembourg, Austria, and the Czech Republic), Ireland, and the United Kingdom (UK) are considered. To account for regional characteristics and to provide more accurate insights, Norway is divided into five bidding zones (NO1-NO5). This approach refers to previous work [16] and is further described in Section III.

As computational complexity increases with the number of considered hours per year, the time-series reduction method by Gerbaulet and Lorenz [17] is applied. This algorithm reduces the time-series based on every n^{th} hour as specified by the user. Afterwards, the time-series is smoothed out and scaled up with a discontinuous non-linear program. Here, we use a time-series based on every 200^{th} hour.

In this study, two decarbonization scenarios are investigated. *BASE* refers to a business-as-usual case, whereas the scenario Offshore Node *(OFF-SN)* accounts for current plans of the Norwegian government to introduce 30 GW of offshore wind by 2040 into the Norwegian continental shelf [2]. For the latter case, a separate offshore region (node) is created that features offshore wind generation. It is assumed that the offshore capacity expansion will be linear from 2025 to 2040. Afterwards, this level will be kept until 2050. The location is based on the planned wind farm Sørlige Nordsjø II [2], which is 276 kilometers offshore from NO2. In this analysis, the offshore node can only be connected to NO2 and all other Norwegian regions cannot invest in offshore wind.

In the light of the current release of potential offshore wind areas in Norway [18], this setup does not represent a realistic system configuration. However, it serves as a starting point to gain first insights into the impacts of offshore wind integration into Norway's energy system.

III. DATA AND DISAGGREGATION OF THE NORWEGIAN ENERGY SYSTEM

The input data for the model is primarily derived from the EU-funded project OpenENTRANCE [19]. In this project, four different pathways for a decarbonized European energy system in 2050 are defined. These scenarios provide a comprehensive collection of data for renewable generation, load, and techno-economic parameters. In this study, the Gradual Development (GD) scenario is used for *BASE* and *OFF-SN*. The GD scenario assumes an equal contribution of technological, policy, and societal effort towards achieving a 2-degree limitation by 2050. It represents a rather moderate pathway since all the other scenarios aim for a 1.5-degree limitation by 2050. In the model, the 2-degree target is implemented as a carbon emission limit. In addition, the GD scenario assumes investment cost reductions in renewable energy technologies, which are presented in Tab. I.

TABLE I
TOTAL CAPITAL COST IN [M€/GW]. [20]

Year	2018	2020	2025	2030	2035	2040	2045	2050
PV	1020	610	514	450	380	327	295	267
Wind Onshore	1250	1150	1060	1000	965	940	915	900
Wind Offshore	3500	2636	2200	1936	1800	1710	1641	1592

Further improvements are made to obtain a more detailed representation of the Norwegian energy system. In Tab. II, regional shares of Norway's population, industry, and land area are given. These are used to disaggregate the exogenous demand time-series for power, buildings, transportation, and industry. We assume a strong correlation between population and the demand for power, buildings, and transportation. This approach is in line with the methodology applied by NVE [21]. In contrast, the industrial energy demand distribution is based on the energy consumption of energy-intensive companies in Norway [21].

TABLE II
REGIONAL DISTRIBUTION OF THE TOTAL NORWEGIAN POPULATION, LARGE INDUSTRY, AND LAND AREA

Region	Population	Industry	Land Area
NO1	42%	5%	15%
NO2	24%	28%	14%
NO3	14%	32%	23%
NO4	9%	19%	41%
NO5	11%	17%	7%

Within GENeSYS-MOD, the trade costs for energy carriers depend on the distance between the geographic centers of each region. This approach is applied for NO1-NO5 and all parameters related to resource potentials are divided using the land area shares from Tab. II. Data on power trade capacities are available in more detail and thus rely on the Net Transfer Capacities published by Statnett[1].

In addition, the nodal potentials for onshore wind (42 GW) and offshore wind (159 GW) are distributed based on a study conducted by SINTEF [22]. This report found that NO3 and NO4 exhibit the highest wind potentials. Furthermore, data from the Norwegian Petroleum Directorate [23] is used to allocate thermal generation units.

IV. RESULTS AND DISCUSSIONS

In this section, the main results of both scenarios are described. To gain a comprehensive understanding of the driving forces behind the model, the total discounted costs and the total energy demand are analyzed. Afterwards, the installed capacities for the Norwegian power sector are presented. Finally, power trade within Norway is examined.

The total discounted costs for the *BASE* scenario are 13.204 billion EUR and the costs for the *OFF-SN* scenario are 13.123 billion EUR, which are 0.5% lower. At first glance, these results may seem counter-intuitive. However, the offshore wind potentials in *BASE* are mainly located in the north of Norway, while in *OFF-SN*, the offshore node is close to the south of Norway and central Europe, where there is existing transmission infrastructure. Therefore, if conditions for connection are in place, offshore wind can potentially reduce total costs for the entire European energy system. However, in the case of Norway, the total discounted costs associated with *OFF-SN* are 5% higher (290 billion EUR) than in *BASE* (275 billion EUR).

In Fig. 1, the total energy demand is illustrated and the model-endogenous power consumption is expressed as a share of the total energy demand.

According to the figure, the demand in Norway varies significantly across different regions, with the northern parts having the lowest demand and the central and southern regions exhibiting the highest demand. However, there is a common downward trend until 2050, largely driven by the assumptions behind the GD scenario [19]. This trend is in stark contrast to the rising share of electrical power in the total energy demand, emphasizing the sector electrification's critical role in achieving carbon reduction targets. In particular, in *OFF-SN*, the share of electrical power increases linearly and is slightly higher compared to *BASE*. This reflects the introduction of offshore wind between 2025 and 2040.

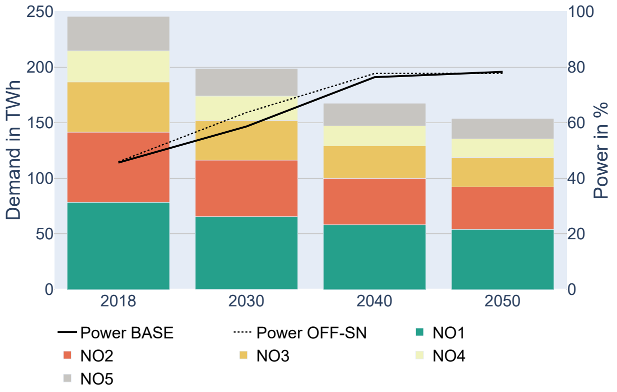

Fig. 1. Development of total energy demand for Norway in TWh.

By 2050, both scenarios project a power demand of 140 TWh (79%), which indicates that the technical limit of electrification has been reached. However, according to Statnett [24], the electricity demand in 2050 will range between 190 TWh and 300 TWh. The disparity between these results can be attributed to different scenario assumptions, particularly with regard to energy demand reductions and carbon emission limits.

The increased electricity demand has a significant impact on the installed capacities in the Norwegian power sector, as shown in Fig. 2.

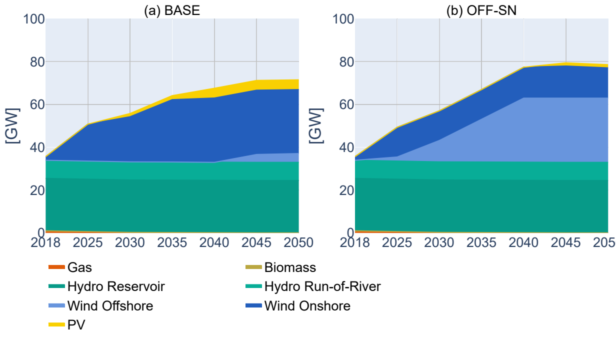

Fig. 2. Installed Capacities for Norway in GW

In both cases, hydropower remains one of the largest renewable technologies in terms of capacity, although the potential for new capacity is limited. Therefore, the combination of hydropower and other renewable technologies such as solar and wind is the most cost-effective strategy to meet the increasing demand for low-carbon electricity and to replace existing natural gas supplies.

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[1] https://www.statnett.no/en/

In *BASE*, the projected renewable energy shares for 2050 show a significant contribution from onshore wind at 42%, while offshore wind and solar contribute at 6% each. This reflects the challenges these technologies face in terms of investment costs and resource potential. By contrast, *OFF-SN* allocates 38% to offshore wind, 18% to onshore wind, and 2% to solar power. Hence, the introduction of offshore wind has a significant impact on the distribution of investments, leading to a 54% decrease in onshore wind and solar combined.

Although the total installed capacity in *OFF-SN* is higher than in *BASE*, solar and onshore wind remain in the 2050 energy mix. There are several reasons for this, including the possibility of curtailment of renewable energy sources due to grid constraints or a lack of storage capacity, which can lead to an under-utilization of offshore wind.

Therefore, further analysis of regional factors is required to understand these differences. This includes an examination of the installed capacities in each bidding zone in *OFF-SN*, which is shown in Fig. 3. Additional capacities from *BASE* are overlaid as dashed lines.

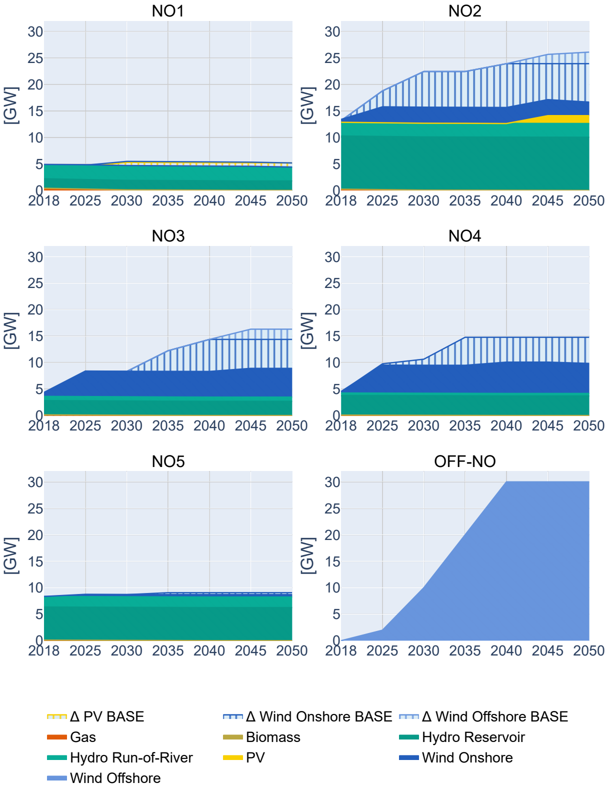

Fig. 3. Installed Capacities for the Norwegian bidding zones in GW

The deployment of offshore wind has little impact on the installed capacity levels in NO1 and NO5 because the potentials for wind and solar are poor in these regions. However, in NO2, NO3, and NO4, the corresponding levels for solar power and wind are up to 28% lower in *OFF-SN* compared to *BASE* in 2050. The reduction is most significant in NO2, which has a direct connection to the offshore node. Despite the potential for additional onshore wind capacity in NO3, offshore wind is still introduced by 2040 in *OFF-SN*, highlighting the growing importance of this technology in meeting Norway's energy needs and reducing carbon emissions.

In addition to the total system costs, the power demand, and the installed capacity, it is worth analyzing how power trade in 2050 is affected by 30 GW of offshore wind capacity. Note that this study still includes the NO5-UK connection and does not take into account the rejection of *NorthConnect* as announced by March 2023. Fig. 4 illustrates the electricity trade in TWh in *OFF-SN* and the corresponding percentage change from *BASE*. Orange arrows indicate an increase relative to *BASE*, while green arrows indicate a decrease relative to *BASE*.

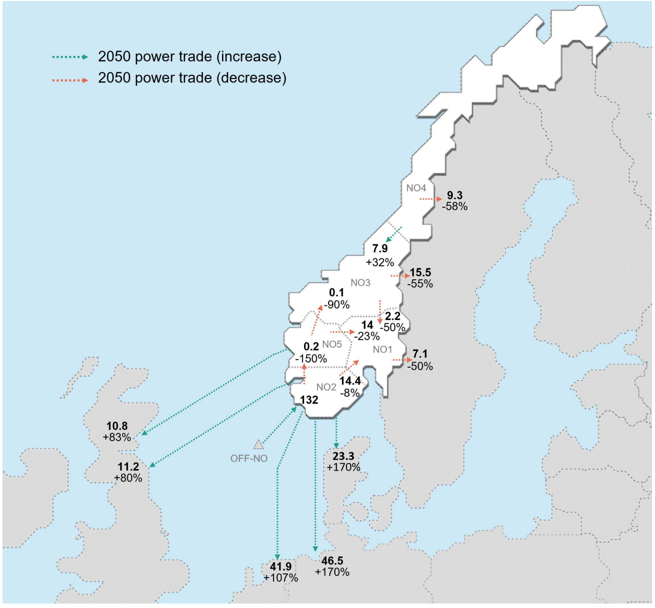

Fig. 4. Power Trade in 2050 in TWh. Green arrows indicate an increase in power trade compared to *BASE*, while orange arrows indicate a decrease in power trade. The map is based on [25].

As shown in Fig. 4, the introduction of offshore wind does not significantly affect the direction of exchanged electricity, but rather the amount of electricity traded. In particular, exports to Sweden from NO3, NO4, and NO1 experience a notable decrease due to the lower renewable capacity and production in NO3 and NO4 compared to *BASE*. As NO4 still has more renewable generation capacities than NO3, it rather exports to NO3 than to Sweden due to shorter distances and corresponding costs. Another important difference between *BASE* and *OFF-SN* is the role of NO1. In *BASE*, NO1 serves as a critical transit point for the export of renewable energy from NO3 and NO4 to Sweden. Consequently, the introduction of offshore wind leads to an overall decrease in both imports and exports of NO1. Despite these changes, the net trade balance for this region remains the same.

Moreover, there is an increase in exports to countries bordering the southern part of Norway, including the UK, the Netherlands, Germany, and Denmark, where the volume of trade almost doubles compared to *BASE*. The geographical distance and the existing infrastructure favor offshore wind exports to these regions. As a result, Norway's net export position improves by 57% compared to *BASE*. Future studies will investigate additional offshore nodes in the north of Norway to assess their geographical impact on the grid design.

V. Conclusion and Future Work

Norway is a frontrunner in the electrification of the heating and transport sector. However, future projections of electricity demand indicate significant electricity demand emerging in the Norwegian power system. Following the ongoing opposition to onshore wind power development and limited potential for other sources of electricity production, offshore wind is a promising technology to cover the future electricity demand. In this article, we investigate the impact of large-scale offshore wind integration into the Norwegian energy system. The Norwegian energy system disaggregation results indicate how regional conditions can impact the future energy system. In general, the addition of 30 GW offshore wind causes a 54% decrease in solar power and onshore wind capacity combined. It would thus indicate that, despite the installation of large amounts of offshore wind, it is still profitable to have some amount of onshore wind in the system; and that offshore wind would not be sufficient to resolve the debates about onshore wind installation. However, it is still necessary to assess different scenarios such as the impact of connecting the offshore node to different countries or the impact of the ambitious offshore goals of other countries around the north sea.

The results presented here are conditional to a number of assumptions and model limitations that may be further explored. There is no stochasticity included in the hydropower inflow or the solar/wind series, there is only one offshore wind capacity location and connection scenario considered and there is no sensitivity performed on the technology costs for the onshore or offshore wind capacities. These are potential points to look into for further analysis of the introduction of large amounts of offshore wind energy in the Norwegian energy system.

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Disaggregation manual for GENeSYS-MOD

This is a quick guide on how to disaggregate countries in GENeSYS-MOD. This is not a guide for introducing new regions, this is just for splitting up pre existing regions in GENeSYS-MOD.

Data needed.
- Centroid of each new region
- Power and gas line transmission capacities to the other regions in the model
- Population of each new region
- Industry demand of each new region
- Location of residual capacity, this can be based on Population on Industry numbers to split the residual, however for the more prevalent technologies, RES, one should use more accurate numbers

Sheets:

Trade Route:
Insert straight line distance between the centroids of regions for new regions.

Trade Cost:
Use the formula from the excel sheet. Its based on the distance from trade route.

Trade Capacity:
Add the transmission capacity of power between regions in 2018, also add the gas pipeline capacity.

Trade Capacity Growth Costs:
This is the same for every region, so just copy paste.

Growth Rate Trade Capacity:
This is the same for every region, so just copy paste.

Regional Annual Emission Limit:
This is the same for every region, so just copy paste.

Emission Penalty:
This is the same for every region, so just copy paste.

Specified Annual Demand:
Base this as percentages from the values in GENeSYS-MOD
- Power: Population
- Mobility Passenger: Population
- Mobility Freight: Population
- Heat Low Residual: Population
- Heat High Industrial: Industry Power Demand
- Heat Medium Industrial: Industry Power Demand
- Heat Low Industrial: Industry Power Demand

Reserve Margin:
This is the same for every region, so just copy paste.

Variable Cost:
This might have something defined for a region, should just use the same value in that case.

Residual Capacity:
This is split into different kinds of technology this is the overview ofer the split, some technologies will not play as big a role
in the model so not everything is the most accurate, for example accuracy in blast furnace capacity is no

t prioritized as much as onshore wind
capacity.
CHP(Combined Heat and Power): Industry Power Demand
D(Dummy/Storage): Based on related residual technology
FRT(Freight): Population
HHL(High Heat Load): Industry Power Demand
HLI: Industry Power Demand
HLR: Population
HML: Industry Power Demand
P(Power): Can be based upon Industry Power Demand, however would be more accurate to split by plants.
PSNG(Passanger): Population
RES(Renewable Energy Source): Should be based on existing capacity as RES technology plays such a huge part in the energy mix in the model.
X: Industry Power Demand(double check)

Availability Factor:
If the region has hydro power this should be copied

Total Annual Max Activity:
Come back to this

Total Annual Max Capacity:
A(Area): Population
RES: Use the same split as before

NB! Some technologies have 999999 max capacity, keep this if that is the case.

Model Period Activity Max Limit:
Come back to this

Regional CCS Limit:
Uses the same split as Model Period Activity Max Limit

Regional Base Year Production:
This sheet follows the Residual Capacity sheet, so use the same split. Will be mostly Industry Power Demand

ModalSplitByFuel:
Copy the values from the node being disaggregated

Offshore node manual for GENeSYS-MOD

Quick Guide for adding new offshore nodes for GENeSYS-MOD

The datafile:

Sets:
Add new node to region column.

TradeRoute:
Add new node to both row and column. Add value of distance from the node to centroid of connected region. The value is the straight line distance. You Only need the distance for Power. ETS is constant at 1.

TradeCosts:
For offshore the only thing to add is the distance and the price for ETS and Power. Price for ETS and Power is 0,01.

TradeCapacity:
The start year is 2018, so for the vast majority of offshore wind farms there will not be introduced any new values here. If there is then just add the capacity of the line in GW for the correct connection

TradeCapacityGrowthCosts:
Constant Values, so just copy paste the other regions

GrowthRateTradeCapacity:
Same as Above

RegionalAnnualEmissionLimits:
Add the same limits, there has been introduced limits in some datasets, if this is wanted calculate the new limits.

EmissionPenalty:
The penalties are universal, so just copy paste for the new regions

SpecifiedAnnualDemand:
The Demand of the offshore node is zero, so just put zero here.

ReserveMargin:
CopyPaste

CapitalCost:
Here one can define the cost of offshore for the region, This might be interesting for sensitivity analysis
Also, one should reduce the cost, as we get a doubling effect from the new trade capacity and grid connection costs
Baked into the existing offshore tech prices.

ResidualCapacity:
This is set in the gms code, however one should copy existing offshore node values to be sure
If There is residual capacity for offshore wind if you're removing from existing region, be sure to add this and remove from original node.

AvailabilityFactor:
Probably unecesarry, however copy paste for consistency with what already works.

AnnualMaxActivity:
This is zero accros the board, so just copy paste

TotalAnnualMaxCapacity:
This sets the upper bounds for capacity expansion and should therefore be discussed
Everything else is zero for offshore wind

ModelPeriodActivity:
This is left blank as offshore does not utilize any of the technologies

TotalAnnualMinActivity:
This is either left to the users whishes, a lower bound for capacity expansion can be set here, this means that if
One wants to force expansion this is where one sets it.

RegionalCCsLimit:
Left Blank

RegionalBaseYearProduction:
Copy Paste old offshore nodes, this is all zero as the production for the set technologies are zero.

ModalSplitByFuel:
Copy Paste old offshore node, this can maby be zero as there is no mobility, however it has no effect on the results if there are values here,
so just copy paste for consistency.

in the Weather data file

So for almost all sheets you can just use whatever value, the model can not build anything other than offshore wind for the offshore nodes, so it does not
matter. The sheets that need new series are the offshore sheets, so.

WIND_OFFSHORE_SHALLOW, WIND_OFFSHORE_DEEP, WIND_OFFSHORE and WIND_OFFSHORE_BASE

Use the same series for all, just change what technology can be allowed to be built in the maxannualcapacity sheet.

in GAMS, below are the necesarry gms files

genesysmod_subsets:
Add the new offshore nodes to both offshore_regions ans All_except_Offshore_Nodes sets

So the data needed for introducing new offshore nodes are as follows:

1. Wind series for the placement of the farms
2. Location of the farms so one can calculate distances
3. Capacity plans, this makes it so one can introduce upper and lower bounds if wanted
4. The dept, this is so it is possible to disable different kind of offshore technology in the node, realistically a farm will be all
 shallow, deep etc.

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