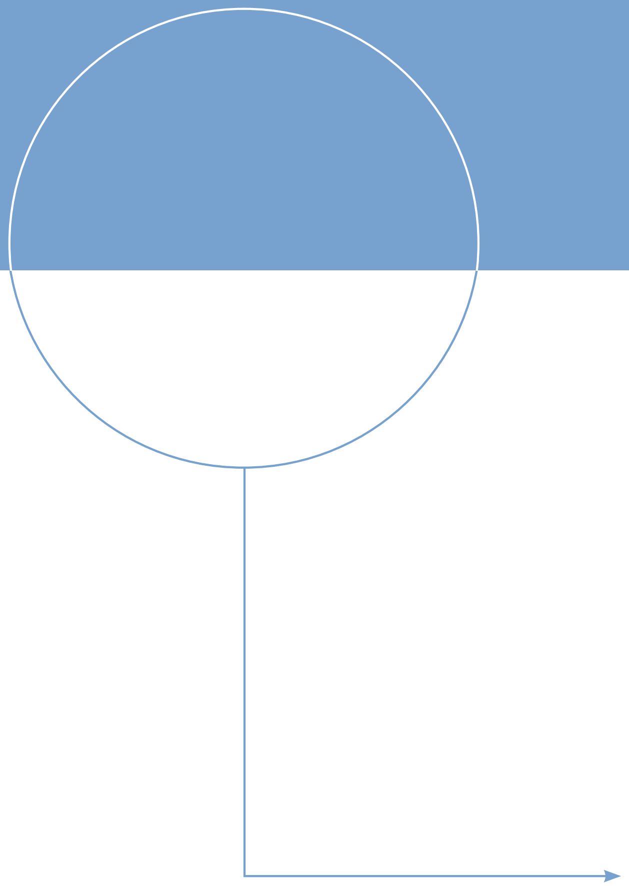

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Aksel Holbek Sørbye, Signy Undine Dost Weisz

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

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Aksel Holbek Sørbye
Signy Undine Dost Weisz

Master of Energy and Environmental Engineering	
Submission date:	June 2021
Supervisor:	Hossein Farahmand, ELKRAFT
Co-supervisor:	Ingeborg Graabak, SINTEF Energy Research Sarah Schmidt, SINTEF Energy Research

Norwegian University of Science and Technology
Department of Electric Power Engineering

Abstract

There is a pressing need to decarbonize the world's energy system to avoid the worst effects of climate change. However, developing reliable energy system models with results that can be used for decision-making in the energy transition is challenging. The H2020 openENTRANCE project aims to respond to this challenge by developing and using a transparent modeling platform to assess decarbonization scenarios for Europe [1]. The openENTRANCE project has developed four scenarios to assess low-carbon developments complying with the Paris Agreement climate goals. These scenarios are modeled using the Global Energy System Model (GENeSYS-MOD) with 30 European regions until 2050, including Norway.

The following research questions are studied in this thesis:

- Can the openENTRANCE implementation of GENeSYS-MOD be used to get useful insights about the future Norwegian energy system?
- Can the insights for the Norwegian energy system be improved by disaggregation?

These questions are answered by verifying the openENTRANCE implementation of GENeSYS-MOD, validating the Norwegian dataset, and implementing the dataset improvements in GENeSYS-MOD to gain a better representation of the Norwegian energy system. The Norwegian dataset is disaggregated into the five Norwegian bidding zones to gain better regional insight of the Norwegian energy system.

Useful insights include the rapid decline of Norwegian oil and gas exports due to decommissioning of the petroleum sector within the near future in the European decarbonization. Photovoltaic (PV) and wind power show to become important low-cost energy sources in the Norwegian energy transition. Hydrogen shows to become an important energy carrier to decarbonize the transportation and industrial sectors, and certain Norwegian regions have the potential to become important hydrogen exporters to neighboring countries.

Shortcomings include the industrial sector modeling. Major Norwegian industries include oil and gas extraction and process industries such as aluminum production. These cannot be represented using the steel industry-based assumptions currently in the model.

Findings indicate that offshore wind may be an alternative if the strict onshore wind policies remain in Norway, or if the industrial power demand increases due to the commissioning of new power-intensive industries. Further work can include exploring these indications by introducing onshore wind policies in the model, and by improving the modeling of the industrial sector for Norway by introducing additional industrial demands for power and hydrogen.

Sammendrag

For å unngå de verste konsekvensene av klimaendringene, blir det stadig viktigere å avkarbonisere verdens energisystem. Det er imidlertid utfordrende å utvikle pålitelige energisystemmodeller med resultater som kan brukes i investeringsstrategier for det grønne skiftet. openENTRANCE-prosjektet forsøker å løse utfordringen ved å utvikle og bruke en åpen modelleringsplattform for å analysere avkarboniseringsscenarier for Europa [1]. openENTRANCE-prosjektet har utviklet fire scenarier for å analysere lavkarbonutviklinger som samsvarer med klimamålene i Parisavtalen. Disse scenariene modelleres med energisystemmodellen GENeSYS-MOD for 30 europeiske regioner mot 2050, inkludert Norge.

Følgende forskningsspørsmål undersøkes i denne oppgaven:

- Kan openENTRANCE-implementeringen av GENeSYS-MOD gi nyttig innsikt om det fremtidige norske energisystemet?
- Kan innsikten om det norske energisystemet forbedres ved å dele opp i mindre regioner?

Disse spørsmålene besvares ved å verifisere openENTRANCE-implementeringen av GENeSYS-MOD, validere det norske datasettet, og implementere datasettforbedringene i GENeSYS-MOD for å oppnå en forbedret representering av det norske energisystemet. Det norske datasettet blir deretter delt opp etter de fem norske kraftprisregionene for å oppnå en bedre representering av energisystemet på et regionalt nivå.

Nyttig innsikt innebærer at norsk olje- og gasseksport i stor grad vil minke grunnet avviklingen av petroleumssektoren i nær fremtid i den europeiske avkarboniseringen. Sol- og vindkraft blir viktige energiressurser i det norske energiskiftet. Hydrogen kan bli en viktig energibærer for avkarbonisering av transport- og industrisektorene, og enkelte norske regioner vil kunne bli viktige hydrogeneksportører til naboland.

Det ble funnet svakheter i industrisektormodelleringen til GENeSYS-MOD. Viktige norske industrier er olje- og gassutvinning og prosessindustrier slik som aluminiumsproduksjon. Disse industriene kan ikke representeres ved de stålindustribaserte antagelsene som foreløpig brukes i GENeSYS-MOD.

Resultatene indikerer at havvind kan bli et gunstig alternativ dersom det forblir politisk utfordrende å bygge ut landbasert vindkraft, eller dersom kraftbehovet i industrien øker som følge av nye, kraftintensive industrier. Videre arbeid kan innebære å utforske disse indikasjonene ved å introdusere norsk vindkraftpolitikk i modellen, og ved å forbedre industrisektormodelleringen for Norge ved å legge til industribehov for kraft og hydrogen.

Preface

This Master's Thesis concludes the authors' Master of Science (MSc) degrees in Energy and Environmental Engineering with the Department of Electric Power Engineering at the Norwegian University of Science and Technology (NTNU). This thesis is written under the supervision of Associate Professor Hossein Farahmand with the Department of Electric Power Engineering at NTNU, and co-supervision of SINTEF Senior Researcher Ingeborg Graabak and SINTEF Researcher Sarah Schmidt. We have been engaged in the research and writing of this thesis from January to June 2021. The process and results of this thesis will be presented at the openENTRANCE consortium meeting on June 22, 2021. Model improvements will be used in the Autumn 2021 GENeSYS-MOD version release. A journal article summarizing the thesis' work and contribution will be submitted for review following the thesis submission.

The work presented in this thesis is a continuation of our research project conducted in the Autumn of 2020 which analyzed the modeled Norwegian power sector in the openENTRANCE implementation of GENeSYS-MOD. This thesis implements some of the suggested modifications from the research project, and continues the work of verifying, validating, and improving the openENTRANCE dataset. Since the work is a continuation of our research project, certain sections from that project have been used. These include the literature review in Chapter 3 and parts of Chapter 4 describing the openENTRANCE scenarios.

We wish to express our sincerest appreciations to our main supervisor, Hossein Farahmand, for supporting us in this thesis, providing useful feedback along the way, and motivating us to work hard. The weekly discussions have helped us develop a deeper understanding of the work we have been doing, and Hossein's enthusiasm and positivity has been greatly appreciated.

We also wish to express our deepest gratitude to Ingeborg Graabak and Sarah Schmidt at SINTEF. They have both contributed with invaluable insights throughout the engagement of this thesis and preceding research project. We would like to thank Ingeborg for providing openENTRANCE insight, and necessary datasets from TIMES, as well as many other useful reports and source material. We would like to extend appreciations to Sarah for setting up an open communication line with the GENeSYS-MOD developers at TU Berlin, enabling a streamlining of the verification and disaggregation efforts presented in this thesis.

We would like to thank Konstantin Löffler and Karlo Hainsch at TU Berlin for invaluable discussions and insights in the model validation and disaggregation efforts. We would also like to thank Julian Straus and Lars Hellemo at SINTEF for discussions and insight regarding Norwegian process industries and gas infrastructure. Last but not least we want to acknowledge the support of our families.

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Acronyms

BEVs Battery Electric Vehicles.

CCS Carbon Capture and Storage.

CO_2 carbon dioxide.

DAC Direct Air Capture.

DT Directed Transition.

ENTSO-E European Network of Transmission System Operators for Electricity.

ETS Emissions Trading System.

EU European Union.

EVs Electric Vehicles.

GAMS General Algebraic Modeling System.

GD Gradual Development.

GDP Gross Domestic Product.

GENeSYS-MOD Global Energy System Model.

GHG greenhouse gas.

HHI Heat High Industrial.

HLI Heat Low Industrial.

HLR Heat Low Residential.

HMI Heat Medium Industrial.

IEA International Energy Agency.

LCOE Levelized Cost of Electricity.

NPD Norwegian Petroleum Directorate.

NTC Net Transfer Capacities.

NTP National Transportation Plan.

NVE Norwegian Water Resources and Energy Directorate.

openENTRANCE open ENergy TRansition ANalyses for a low-Carbon Economy.

OSeMOSYS Open-Source Energy Modeling System.

PHS Pumped Hydro Storage.

PV Photovoltaic.

SC Societal Commitment.

SSB Norwegian Bureau of Statistics.

TF Techno-Friendly.

TSO Transmission System Operator.

TU Berlin the Technical University of Berlin.

TØI Institute of Transport Economics.

Glossary

scenario "In general, a scenario is a counterfactual development, usually compared to a baseline or reference" [2]. In the context of this thesis, a scenario is the hypothetical development of the European energy system along with the development of factors that shape the energy system. Scenarios are described by parameters that define which different strategies, policies, or technological potentials that can be applied to given energy system factors.

validation Validation can be defined as "the the act of confirming something as true or correct" [3]. In this thesis, validation is the process of confirming if the GENeSYS-MOD input data and base year outputs correspond with base year statistics from reliable sources.

verification Verification can be defined as "evidence that establishes or confirms the accuracy or truth of something" [4]. In this thesis, verification is the confirmation of whether the results provided by openENTRANCE can be reproduced by independent runs of GENeSYS-MOD.

Chapter 1

Introduction

Mitigating the effects of climate change and global warming is one of the biggest challenges we are facing today [2]. To avoid severe environmental and financial risks, the 2015 United Nations Climate Change Conference COP 21 in Paris agreed that the global temperature increase must be limited to 2.0°C, preferably 1.5°C, compared to pre-industrial levels [5]. Limiting greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), is essential for compliance with this agreement [2]. The European Commission intends for Europe to lead the way in the global climate change mitigation by setting goals to reduce GHG emissions by at least 55% by 2030 compared to pre-industrial levels [6]. The largest share of GHG and CO_2 emissions stem from the energy sector, particularly the power, transportation, heating, and manufacturing sectors [7]. Hence, to comply with the goals set by the European Commission and the Paris Agreement, it is vital to find ways toward decarbonizing the energy system.

Insights and opinions on how energy systems should develop to reach the international climate goals can be based on the results of cost-minimizing optimization modeling of decarbonization scenarios. However, these models and the accompanying data used are not always openly accessible. The H2020 project open ENergy TRansition ANalyses for a low-Carbon Economy (openENTRANCE) intends to develop and use an open and transparent modeling platform for assessing low-carbon scenarios [1].

The openENTRANCE project aims to help actors with decision making by "shedding light on the implications and economic costs associated with the different energy pathways that Europe could take towards its climate goals" [1]. The project also aims to integrate new challenges posed by the energy transition in a way that current models used to plan and support energy policies do not fully incorporate. These challenges include integrating factors for determining power generation such as decentralization, variability, and flexibility services and integrating factors for determining power demand such as the behavior of individuals and communities. [1, 8]

1.1 Motivation for Modeling with GENeSYS-MOD

One of the main modeling tools used in the openENTRANCE project for modeling decarbonization scenarios is the energy system model GENeSYS-MOD. It is an open-source, open-data, long-term multi-sectoral energy system model capable of sector coupling [9].

Furthermore, the model features a high level of sectoral detail, which facilitates the modeling of detailed global decarbonization scenarios. GENeSYS-MOD is therefore well-suited for running the scenarios developed through the openENTRANCE project. GENeSYS-MOD is also designed with the ability to model new regions, including the disaggregation of larger geographical areas. These factors make GENeSYS-MOD suitable for studying the energy system of a country detailed by regions.

Sector coupling allows the model to provide insight beyond what can be gained from the traditional approach of modeling the power sector isolated. As the Norwegian energy system is often modeled with a power sector focus, analysis with GENeSYS-MOD can provide novel decarbonization insights.

Furthermore, as many existing studies only focus either on Norway or the Nordic countries, it is particularly interesting to analyze Norway in a European context. Trade of energy carriers and resources is currently, and will continue to be, an essential part of the Norwegian energy policy and economy, as it is for most European countries. For this reason, it is important to include cross-regional trade when the goal of the study is to provide policy and economic insights. The openENTRANCE implementation of GENeSYS-MOD, which models 30 European regions and includes cross-regional trade, is therefore an interesting model to study.

The transparency of the openENTRANCE modeling platform makes further reuse, adjustment, and verification of datasets by other actors possible. Thus, decarbonization scenarios for the Norwegian energy system can be modeled, which can be verified and improved by others. Furthermore, the feasibility of the scenario results can be analyzed with regard to current Norwegian energy policies. As the openENTRANCE scenarios in their present version are preliminary and will be further improved for a re-run with GENeSYS-MOD within the near future [10], the suggestions for model and input data improvements in this thesis can be used to further improve the modeling of Norway.

Modeling the Norwegian energy system at a regional level can provide additional insight into regional limitations and potentials. Using a higher spatial resolution can produce information about which regions have the potential for power surpluses, and thus where new power-intensive industries should be located. Regions with power deficits may be analyzed to see where new power capacities are most needed. In addition, flows of energy carriers between regions can provide information about how the regions can collaborate for mutual benefits.

1.2 Thesis Objective and Scope

The objective of this thesis is to analyze scenario-based energy system developments towards 2050 for Norway and the Norwegian bidding zones using GENeSYS-MOD with the scenarios developed through the openENTRANCE project. Modeling the five bidding zones will be done through disaggregating the original openENTRANCE aggregated Norwegian regions. These regions are useful to analyze because the power system is a dominating part of the Norwegian energy system, due to significant levels of electrification in the heating and transportation sectors. Because relevant data is available at bidding zone regional level from sources such as the long-term market analysis from the Norwegian Water Resources and Energy Directorate (NVE) [11], it is possible to analyze these regions separately. The analysis is done through a process of model verification, input data validation and modification, and result validation.

Thus, the following research questions can be formulated:

- **Can the openENTRANCE implementation of GENeSYS-MOD be used to get useful insights about the future Norwegian energy system?**
- **Can the insights for the Norwegian energy system be improved by disaggregation?**

GENeSYS-MOD is a comprehensive, large-scale energy system model which generates an extensive number of results. For this reason, the geographic scope of this thesis has been limited to Norway. Thus, this thesis will analyze the GENeSYS-MOD results for the Norwegian power, industrial, and transport sectors. Furthermore, trade between the Norwegian bidding zones and export to European countries will be analyzed, particularly oil and gas, power, and hydrogen.

1.3 Contribution

The thesis' contribution is to provide insight into decarbonization scenarios for and future developments of the Norwegian energy system at a national and regional level. This has been done by using public reports providing data to disaggregate the Norwegian GENeSYS-MOD input data into the five bidding zones NO1, NO2, NO3, NO4, and NO5. Accounting for regional power market conditions, the aim is to get results that are of higher value for decision-making than what can be obtained by modeling Norway as a single region. The results give indications for the scope of actions that must be taken in Norway to reach the European decarbonization goals.

Furthermore, the results and insight presented in this thesis will be used to further improve the openENTRANCE modeling of Norway with GENeSYS-MOD for their Autumn 2021 model run. The openENTRANCE modeling of Norway has been improved by validating the model input data and base year outputs for Norway, and providing improved input data where available. The results of these input data improvements are presented in this thesis, with an analysis of the effects of these modifications on the results.

1.4 Thesis Structure

Background Chapter 2 presents the Norwegian energy system, how the power, heating, industrial, and transportation sectors are today, and how they are expected to develop. Current and likely future Norwegian energy policies are presented, as well as their impact on the development of the various energy system aspects.

Energy System Modeling Chapter 3 presents literature on energy system modeling. It is explained what energy system models are, and why they are useful. Literature on GENeSYS-MOD is presented, including main model concepts and how GENeSYS-MOD has been used previously to model energy systems.

openENTRANCE Scenarios Chapter 4 presents the openENTRANCE scenarios used for the analyses in this thesis. The scenario development process is described, and the scenario-specific features are detailed. This includes a quantification of the main scenario differences.

Verification, Validation and Modification Process Chapter 5 describes the process of analyzing the results received from openENTRANCE for model verification. Furthermore, the validation process for the input data and base year outputs is described. The chapter also describes which improvements were made to the input dataset for a better representation of the Norwegian energy system.

Case Study: Disaggregating Norway Chapter 6 describes the process of disaggregating Norway into the five bidding zones in GENeSYS-MOD. The disaggregation assumptions made are explained, and observations are presented.

Results and Analysis Chapter 7 presents a selection of GENeSYS-MOD results. The results of the validation process are presented, with a discussion on the validity of the results and the impacts that the model modifications had on the results. The disaggregated Norwegian energy system results are presented, with a focus on results relating to the power sector, mobility, hydrogen production and use, and trade of fuels.

Discussion Chapter 8 discusses the insights gained from the results of this thesis. GENeSYS-MOD modeling limitations and input data challenges are discussed, as well as the assumptions made for the work in this thesis.

Conclusion and Further Work In the final chapters, concluding remarks on which insights can be gained from this thesis are summarized. Finally, recommendations are given for how the model version created in this thesis can be further modified to better represent certain elements of the Norwegian energy system.

Chapter 2

Background: The Norwegian Energy System

The main sectors in Norway that require energy can be divided into manufacturing industries, transportation, households, and service industries [12]. Figure 2.1 shows that in all these sectors besides transportation, most of the demand is supplied by electricity. In the industrial manufacturing sector, electricity is a major demand for process industries [13]. In households and services, a large share of the total energy consumption is used to supply heating demands. The transportation sector's energy consumption mainly consists of fossil fuels, although the sector has become more electrified in recent years.

In this chapter, the current Norwegian power system and the energy system sectors industry, transportation, and heating will be presented in a Norwegian context. Each sector will be described, and the major energy demands explained. Current and likely future energy system policies will be presented, as well as likely developments of the energy system as a result of these.

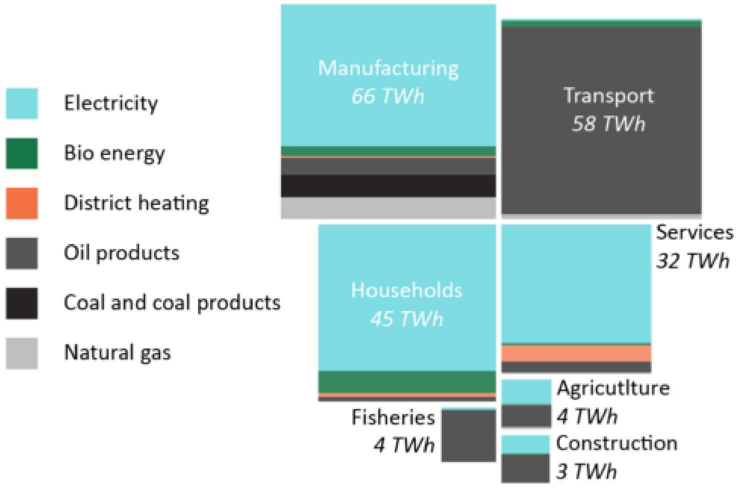

Figure 2.1: Energy consumption of different sectors in Norway in 2015 Source: OED [12]

2.1 Power System

Norway's power system is highly decarbonized, with approximately 98% of its power production being provided by renewable sources [14, 15]. In a normal production year, about 89% of the nation's power is produced from hydro, about 9% is wind power, and the remaining is produced by thermal energy [14]. This gives Norway the highest share of renewable electricity production in Europe, as well as the power sector with the least emissions [16].

Norway also contains half of Europe's reservoir storage capacity. This capacity is sufficient to cover 70% of Norway's annual power consumption in an average year [16]. Furthermore, the investments into wind power have increased substantially, partly due to increased profitability, which will further increase Norway's renewable power production capacity [14, 16]. Another key aspect of the Norwegian power market is its close integration with the Nordic system and by extension to the rest of Europe [16].

2.1.1 Energy Sources

Hydropower has always been the main source of electric power in Norway. It currently accounts for 88% of the country's installed capacity with a normal annual production of 136.4 TWh. Norway's power production therefore heavily depends on annual inflow from precipitation and glacier melting. This is significantly different from most countries in Europe, which depend on thermal power to achieve power security. More than 75% of Norwegian power production capacity is flexible, primarily because of the large share of hydropower, which can be rapidly regulated when needed at low costs. [16]

Wind power is relatively new to Norway, with the first wind farm installed at Smøla in 2002 [16]. In recent years, there have been heavy investments into onshore wind, with the annual wind production growing from 2.1 TWh in 2016 to 9.9 TWh in 2020 [17].

Thermal power is used mainly by large industrial installations with their own power plants [16]. Historically, annual thermal power production in Norway has been relatively stable at around 3.4 TWh [16].

There are currently no large-scale offshore wind installations in Norwegian waters [18]. The most prevalent reason is that the Levelized Cost of Electricity (LCOE) of offshore wind is approximately USD 0.115/kWh (as of 2019), which is significantly higher compared to onshore wind, which has an LCOE of about USD 0.053/kWh [19]. Traditionally, Norwegian companies involved in offshore wind have reported that the industry has been considered risky due to market-related reasons [18]. These reasons include a lack of familiarity within sales processes, contract design, customer relations, and regulations within the offshore wind industry. [18]. However, significant research and developments have been undertaken in recent years, which will be further discussed in section 2.5.4.

2.1.2 Future Developments

The Norwegian power demand is expected to grow significantly in future years. In a 2018 study from NVE, the Norwegian power consumption is calculated to increase from 133 TWh in 2016 to 157 TWh in 2035 [20]. This is mainly due to an expected large degree of sector coupling through electrification. Reasons for this projected increase include plans to build new and expand existing industrial plants and plans to substantially electrify manufacturing processes and oil platforms [20, 21]. These developments are calculated to give an increase of 14 TWh in 2035 compared to 2016 [20]. The study also shows that the annual transport sector power consumption could grow by 8 TWh in the same time frame [20]. Lastly, the emergence of new data centers could require an additional power demand of 3 TWh by 2035. In the residential sector, the power demand is expected to be slightly reduced due to more efficient heating and better insulation.

2.1.3 Bidding Zones

The regional differences in Norway regarding power production and consumption are significant. For instance, the population-dense region around Oslo has a high demand, but relatively low power generation compared to other regions. Power trade between regions enables high-demand areas to import power to cover the load, and low-demand areas to export surplus power. In periods when the power grid capacity is insufficient for trade, bottlenecks occur between regions. Identifying these bottlenecks and defining separate bidding zones on each side helps balance the power market. On the side with a power deficit, the power price may be set higher than on the side with a surplus. The consequent power flows from areas with low prices to areas with high prices contribute to supplying areas with high demand. In addition to balancing the power flows, these bidding zones can help power producers and consumers locate the areas that are most profitable for new generation capacity or new consumption-heavy industry. [22]

Figure 2.2: Bidding zones

Since March 2010, the five Norwegian bidding zones have been defined as Southeast Norway (NO1), Southwest Norway (NO2), Mid-Norway (NO3), Northern Norway (NO4), and West Norway (NO5) [23]. These are shown in Figure 2.2. The five regions have very different characteristics regarding amount of demand, type of demand, production, and resource availability. For this reason, it is useful to look at these separately when modeling future energy system developments for Norway.

2.1.4 Power Trade

Norway has overall low power prices compared to neighboring countries due to the high availability of reservoir hydro [24]. Power is generated where it is cheapest and flows in the direction it has the largest value [25]. Norway has been a net exporter of around 10 TWh of power annually for the last ten years [22]. Since 1990, new transmission lines to Denmark, the Netherlands, and Sweden have increased the trade capacity by more than 2000 MW [22]. The newly operational line to Germany has increased the capacity by an additional 1400 MW [26]. In addition, underway construction of a transmission line to the UK will further increase the possibilities for power trade [27].

Power trading in the European market enables power to flow from countries with lower power prices to countries with higher power prices [22]. This provides mutual benefits, as the overall costs become lower than if each country had to provide their own energy supplies [22]. For Norwegian consumers, however, the total power prices are expected to increase due to the new trade links to Germany and the UK [13]. This is because the market for surplus Norwegian power increases, which makes it more profitable to export power instead of selling it cheaply to Norwegian consumers.

Flexible Norwegian hydropower is especially favorable now that variable renewable energy sources such as wind have become increasingly widespread in the Nordic countries. When the Nordic wind speeds are high, the power prices decrease due to an electricity surplus. At these times, power producers can retain reservoir water, and cheap power is imported from neighboring countries instead. Furthermore, when wind speeds are low and prices are higher, Norway can export power. [22]

2.2 Heating Sector

The total amount of energy used for low temperature heating (<100°C) in Norway in 2018 was around 73 TWh, which is about one third of all energy use in the country [28]. Around half of the heat demand (38 TWh) is used in residential buildings, while the rest is used in service industries (16 TWh) and manufacturing industries (19 TWh) [28]. The service industries generally have quite similar heating needs as private households, where heating of space and water are the primary demand [12]. Manufacturing industries have additional demands for medium (100-1000°C) and high (>1000°C) temperature heating.

Low temperature heating in Norway is predominantly accomplished with the use of electricity, as illustrated in Figure 2.3 [28]. For this reason, there is little infrastructure in the country for distributing gas, contrary to many other European nations. There are, however, other segments of the energy system that can provide heat by transporting energy carriers to end-users. One of these segments is district heating, which provides around 8% of the required energy to heat buildings and water in Norway [29]. The use of district heating is mostly concentrated in large towns where cheap heat sources, like heat from waste incineration or waste heat from other processes, are easily available and where potential consumers are densely populated [12]. District heating is especially utilized in the service industries, where it supplies around 30% of the heat demand. Another important source for heat production is bioenergy, which supplies around 12% of the low temperature heating demand in Norway [29]. [16]

As shown in Figure 2.3, manufacturing is the only sector in Norway where oil and gas supply a considerable amount of the low temperature heating demand. Because heat can easily be

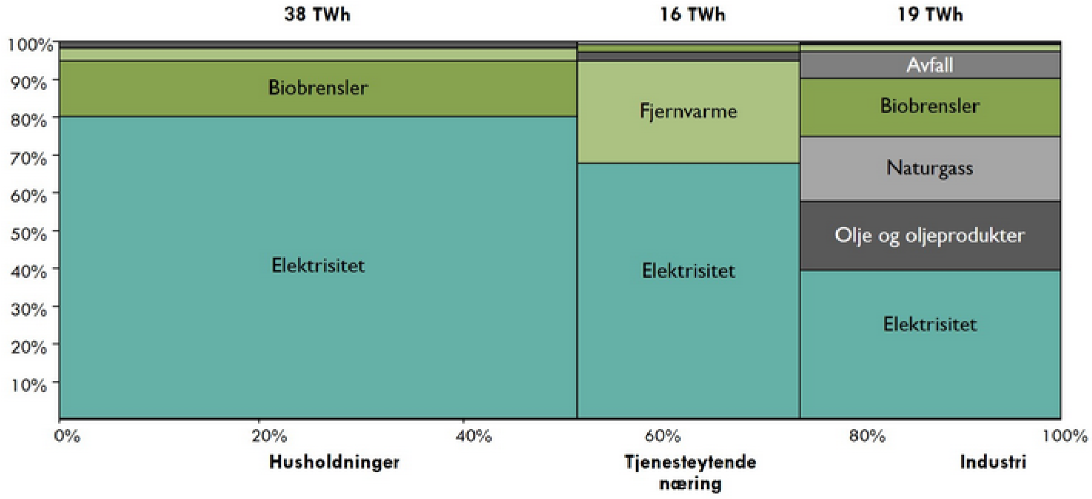

Figure 2.3: Total demand for low heating, split by energy carrier, in different sectors in Norway in 2018. Source: NVE [28]

created from other sources, there is a huge potential for electrification and increased use of biofuels in the sector [30]. In the manufacturing sector, heat with temperatures above 100°C is used in the production of metals, basic chemicals, and cement [12]. However, there is little data available which quantifies the energy used in manufacturing processes specifically for medium and high temperature heating.

2.3 Industrial Sector

The most important export industries for the Norwegian economy are oil and gas production, fish farming, and metal industries [31]. For this reason, decarbonization of these industries will play a significant part in the development of the future Norwegian industrial sector.

Process industries such as aluminum production, mineral fertilizer production, and silicon production are important for Norwegian employment and value creation [32]. In 2013, process industries were responsible for 20% of the total value of Norwegian export [33]. According to the International Energy Agency (IEA), power-intensive aluminum production will continue to increase by about 150% until 2050 due to its increased use in vehicles and buildings [33]. Mineral fertilizer production and consumption will also continue to increase due to its role in creating sustainable global agriculture [33]. Silicon production is expected to continue to increase for its use in electronics and solar panel production [34]. In the decarbonization of certain process industries, such as mineral fertilizer production, green hydrogen will play an important role. This is because hydrogen is essential for its chemical properties in the production of ammonia and methanol [33].

Norwegian oil and gas export supplies 2% and 3%, respectively, of the global demand for these resources [35]. In 2020, this accounted for 42% of the total value of exported goods from Norway [35]. Furthermore, until 25% of the European natural gas demand is supplied by Norway [35]. Natural gas in Europe is used for residential heating, cooking, and gas-fired power plants. For these reasons, oil and gas export is currently important both for the Norwegian economy and as a source of energy security in Europe.

In Europe's decarbonization, Norwegian oil and gas exports are expected to decrease. Thus, to retain today's living standard, it will be necessary to find new export goods which can ensure employment and value creation [36]. With the increase in shares of Battery Electric Vehicles (BEVs) in Europe, the demand for batteries produced with clean energy will also increase [36]. For this reason, battery production is one promising industry for Norway [36]. Data centers are another power-intensive industry which could contribute to Norwegian value creation [37]. New battery production plants and data centers, along with hydrogen production and decarbonizing the aluminum and silicon industries, will require large quantities of power from renewable sources [38]. According to the Prosess21 project, which assesses the future Norwegian industrial potential, 56 TWh extra power production will be necessary to supply these demands, which will require substantial power capacity developments [38].

2.4 Transportation Sector

The transportation sector, which includes road traffic, aviation, shipping, etc., accounts for over 30% of the Norwegian greenhouse gas (GHG) emissions [39]. Road traffic is particularly interesting. While it accounts for over half of these emissions, it is also a sector in rapid change. In 2015, only 2.6% of private vehicles were electric [40]. At the beginning of 2021, 17% of all private vehicles were either battery electric (12%) or plug-in hybrid electric (5%) [40]. This was an increase of 30% and 20%, respectively, compared to the beginning of 2020. Additionally, the number of petrol-fueled and diesel-fueled vehicles decreased by 8% and 3%, respectively [41]. The market shares of battery electric and hybrid electric vehicles are expected to increase even more in the future, which will lead to significant decarbonization of the transportation sector. This trend is showing already, as out of the 141,000 new registered personal vehicles in 2020, 54% were fully electric [41]. The main driving forces for Norway's high penetration of electric vehicles are a combination of tax rules that make it cheaper to purchase them, as well as other incentives put in place by the government such as lower road tolls [42].

In connection with the National Transportation Plan (NTP), the Institute of Transport Economics (TØI) has published a report with projections for domestic passenger transportation between 2016 and 2050 [43]. Of all passenger demand in 2016, 82% was covered by road transportation, 8% by rail, and 10% by air [43]. According to TØI's report, the total transportation demand for passenger kilometers is expected to increase from 55.9 billion passenger kilometers in 2016 to 75.4 billion passenger kilometers [43]. This has to do with an expected 29% increase in number of total trips due to the Norwegian Bureau of Statistics' (SSB) expected population growth [44]. Of these trips, the number of longer trips is expected to increase substantially [43]. However, it is important to note that these projections have been modeled under the assumption that no new measures will be taken to impact transportation demand, such as new policies or incentives [43].

2.5 Energy Policies

According to a white paper published by the Norwegian government in 2016, the Norwegian energy policy towards 2030 aims to focus on economic growth, security of supply, and consequences for our climate to ensure an efficient and climate-friendly energy supply [45]. Security of supply will be maintained through enhanced energy system flexibility and can be achieved with strengthened Nordic energy cooperation, the use of new technologies, and smart energy management systems. Ensuring an efficient and climate-friendly energy supply, that also allows for economic growth, is aimed to be achieved through profitable production of renewable power and by developing and using new technologies for renewables. In addition, stronger integration with other energy markets both in the Nordic region and in Europe is a goal for increased efficiency and economic growth [45]. Thus, the Norwegian energy policy opens for a progressive and innovative development of the future energy system. The policy was developed with the Paris Agreement in mind, and with Norway's legislated goal of reducing emissions by at least 40% by 2030 compared to 1990 levels [46]. This goal was further enhanced in 2019, with the updated goal being to reduce emissions by at least 50%, towards 55% within the same time frame [47].

To ensure the commitment to achieving the Paris Agreement emission reduction target, the Norwegian government presented a white paper in January 2021 describing their proposed climate action plan towards 2030 [48]. In this action plan, it is detailed how the Norwegian society will need to transform in the next years to reduce domestic emissions by 45%, which is an enhancement of the assigned target from the EU of reducing 40% non-ETS (Emissions Trading System) emissions [48]. The government plans that this emission reduction will be met through incentives including increased carbon taxing, financial support for development of new technologies, and initiatives to promote research and innovation [48]. Financial incentives to cut emissions such as predictable carbon taxing will make it easier for industries to plan emission reductions.

2.5.1 Renewable Energy Sources

Due to hydropower's prevalence and valuable contribution of flexibility services, the Norwegian energy policy will keep hydropower as the dominant electricity source [49]. The production and capacity will be further increased by upgrading existing turbines and reservoirs and by building new micro run-of-river power plants [49].

The government stated in the 2016 white paper that the long-term development of profitable onshore wind power would be pursued, due to the low investment costs and high availability of suitable wind areas [45]. Additionally, it was stated that a national framework would be developed to dampen conflicts and contribute with appropriate locations [45]. In 2020, this national framework for approval of onshore wind power was updated to give local communities more authority for declining wind power plant concessions [50]. As a result of this update, no new concessions have been processed since 2019, with the consequence that no new onshore wind installations are expected to be deployed for several years after 2021, presumably not until 2030 [51, 52].

The costs of solar power are decreasing at a faster rate than any other power generation technology and is currently one of the most competitive power generation sources in Europe [53]. Despite comparable efficiencies to southern European nations due to lower temperatures in Norway, solar power has until recently not been seen as profitable [54]. This is mainly due to lower power prices and higher capital costs in Norway compared to other European countries, as well as low levels of subsidies and incentives [54]. However, towards 2030 this is expected to change. The power prices are expected to double, and the capital costs of solar power are expected to decrease by until 40% [54]. Thus, it is likely that solar power will become profitable in the Norwegian power market.

2.5.2 Conventional Energy Sources

Even though most of the Norwegian energy demand is supplied by renewable energy sources, in 2015, fossil fuels were still a significant share of the energy consumption in certain sectors, including transport, industries, agriculture, and households [55]. However, current energy policies are working towards decreasing emissions in these sectors. Since January 1st, 2020, fossil oil has been forbidden to use for heating in buildings [56]. With subsidies in place, this has allowed households to make the switch to renewable heating technologies such as waste-fueled district heating and heat pumps [56].

Currently, fossil fuel driven and hybrid vehicles account for 90% of total road traffic [40], and transport emissions are responsible for 60% of non-ETS emissions [57]. In the white paper presented in January 2021, it was stated that by 2022 requirements will be introduced for zero-emission passenger cars, and by 2025 these will apply to all new vehicles [48, 57]. This is to achieve the government's goal of halving the emissions in the transport sector by 2030 [57]. Furthermore, the government's goal of increasing the CO_2 emission penalties from 590 kr/ton (59 € /ton) today to 2000 kr/ton (200 € /ton) in 2030 will further incentivize the transition to zero-emission technologies in all sectors [48].

2.5.3 Oil & Gas Extraction and Production

The Norwegian government interprets the Paris Agreement such that the responsibility for greenhouse gas emissions lies on the demand side, and not the extraction side [58]. For this reason, the Norwegian energy policies focus very little on attempting to reduce oil and gas extraction [48]. Instead, policies are set in place to reduce Norway's legislated emission responsibilities due to emissions as a direct consequence of extraction and production. The most important incentive for decarbonization through platform electrification is by increasing the carbon taxes significantly, which the government is currently proposing [48, 59].

Oil companies in Norway are highly taxed, which is to ensure that as large as possible share of value creation goes to the state, so that the society can benefit from the industry [60]. However, investment costs can be deducted to increase investment willingness [60]. For these reasons, investment willingness and production activity are currently high on the Norwegian continental shelf, and as of January 2021 were expected to continue to rise in the next years [61]. However, in May 2021, the IEA, which has until now been positive to continued oil and gas extraction, presented a report stating that searching for new oil and gas fields must be halted after 2021 to reach the 1.5 °C climate goal [62].

On June 11th, 2021, the government responded to the IEA development by stating in a press release that "We will facilitate a future-oriented Norwegian oil and gas industry capable of delivering production with low emissions within the framework of our climate policy." [63]. Despite this, continued exploration remains a significant part of the future energy policy, which the government justifies by the need for value creation and employment [63].

2.5.4 Future Technologies

In the Norwegian government's 2021 climate action plan, it is considered paramount that new technologies and solutions are developed to achieve sufficient emission reductions. The government will therefore facilitate developments of Carbon Capture and Storage (CCS), offshore wind, and hydrogen production through subsidies and incentives. With the addition of increased CO_2 penalties, it will become profitable for companies to invest in emission-reducing technologies. [57]

While onshore wind and solar power are generally considered to be the cheapest sources of renewable energy [64], the number of suitable sites for these technologies is limited. There are fewer area restrictions and vast wind potentials at sea, which is why offshore wind power is a technology that could be an important part of future energy systems [64]. In January 2021, the government opened the areas "Utsira Nord" and "Nordsjø II" for offshore wind developments, which could facilitate 4500 MW of power [57].

The challenge with offshore wind power in Norway is that it is currently not profitable, and costs are expected to remain higher than onshore wind for the foreseeable future [11]. Most of the world's installed offshore wind farms use fixed foundation turbines [65]. However, the Norwegian sea areas are deep, and have complicated seabed conditions that are poorly suited for wind turbine foundations [65]. Therefore, most of the offshore wind potential in Norway requires floating wind turbines, which is significantly more expensive than their fixed foundation counterparts [65]. However, the technology is becoming increasingly cheaper, and it is estimated that as CO_2 penalties increases, floating offshore wind will become increasingly favorable compared to conventional technologies [11, 64]. It is therefore expected that offshore wind power will be developed in Utsira Nord and Sørlige Nordsjø II, but not before 2030. [11, 64]

While renewable energy sources have the potential to supply the world's annual power demand many times over, they might not always be able to provide it when it is needed. Electricity is a commodity that must be used the instant it is produced [11]. As intermittent energy sources like wind and sun make up larger parts of the power system, it becomes increasingly important to have flexibility in the system that can capture surplus power and utilize it in hours with low renewable production. One of the promising solutions to supply needed flexibility is the use of hydrogen technologies. [11, 64].

Hydrogen is an energy-dense energy carrier that can be produced by different means, such as natural gas steam reforming or power-consuming electrolysis of water. Electrolysis can quickly be scaled up and down, which means that it can effectively utilize cheap surplus power during peak production. This can also have a stabilizing effect on the power prices, which in turn will make it more profitable to build more solar and wind plants [64]. When the output of renewable sources drops, stored hydrogen can be used in power plants and fuel cells to make up some of the lost production [64]. Furthermore, hydrogen also has the significant advantage of having the potential to decarbonize sectors that are hard to decarbonize, like heavy transport and certain industries that require high temperatures [66]. These factors suggest that hydrogen could play an important role in future energy systems. However, due to the high cost of creating hydrogen through electrolysis, the process is only expected to become commercially viable for large-scale production after 2030 when the technology is cheaper and surplus electricity is available. Until then, the government aims to increase the number of pilot and demonstration projects in Norway to contribute to the development and commercialization of hydrogen [6]. [11, 64]

Carbon Capture and Storage (CCS) technologies could be used to permanently store CO_2 underground to avoid its emission into the atmosphere. CCS technologies have the potential to enable continued use of CO_2-producing processes in industrial sectors without forfeiting the Paris Agreement goals. Examples of such sectors are the cement industry, which stands for around 8% of the world's CO_2 emissions, metal production, and waste incineration. [67]

Norwegian institutions have been researching CCS for decades [67], and the government will continue to support the development of CCS [57]. The goal is to develop cost-effective CCS technologies for large-scale deployment [67]. These efforts have led to the Longship project, which is among the world's first initiatives for storing large amounts of CO_2 from multiple countries [67]. The project's purpose is not only to store CO_2 but also to develop cost-effective CCS technologies that other countries would be willing to use [68]. If the project succeeds, it could also encourage future projects in other countries. This could lead to full-scale CCS making a substantial impact in reducing emissions from power production and industries that make up significant parts of the world's CO_2 emissions [69].

Chapter 3

Energy System Modeling

This chapter aims to provide a foundation for understanding the principles, functions, and applications of the Global Energy System Model (GENeSYS-MOD). Theory on what energy system models are, and why they are useful is presented, followed by a description of the GENeSYS-MOD basic modeling principles. This chapter presents extracts of a more detailed GENeSYS-MOD description and extensive literature review presented in the research project preceding this thesis.

3.1 Definition and Modeling Approaches

An energy system can be defined as all components and information required to produce and distribute the energy that is demanded within a given area [70]. Energy system models are mathematical representations that can be used to analyze different aspects of such systems, often to gain insight regarding the supply and demand of energy [71, 72]. The complexity of these models is heavily dependent on the size of the system being analyzed and the required accuracy of the results [71]. For example, a model describing a single power plant supplying a load in a local area can be less complex and more accurate than a model including all power demands and productions of an entire country.

Generally, energy system models provide cost-efficient solutions for meeting future energy demands [73]. These solutions can serve as guidance for making sound investment decisions and policies. Additionally, energy system models can be used to try to predict the effects of energy policies. They can also be used to simulate the consequences of system developments or configurations [74]. These simulations can alleviate the need to test proposed system changes in real-world conditions, which can be difficult and expensive, if not altogether impossible [74]. For these reasons, energy system models have been used successfully since the 1980s [74]. Due to the vast complexity of energy systems, it is extremely challenging to make a single model that covers all aspects of them accurately. Many different models have therefore been created to address different contexts, scales, and time frames. [74, 75]

There are generally two approaches to follow when modeling energy systems [75, 76]. GENeSYS-MOD uses a bottom-up approach, also called the engineering or techno-economical approach. Detailed technical information about the energy system is used to make these models [75, 76]. This focus on technology means that bottom-up models can be used to predict how policies related to the use of technologies will impact the energy system [77].

The other is the top-down, or macroeconomic approach, where models attempt to represent the economy as a whole for the geographical area in question [75, 76, 78]. As a result, the effects of climate change and energy policies are modeled as monetary units [78]. Both approaches are often used together, which results in hybrid models [75]. These models combine the technical details of bottom-up approaches with the economic considerations of top-down approaches, to gain the advantages and negate the drawbacks of the two approaches [79].

3.2 GENeSYS-MOD for Energy System Modeling

The Global Energy System Model (GENeSYS-MOD) is a linear, cost-minimizing, open-source energy system modeling framework coded in the General Algebraic Modeling System (GAMS). The model was developed by Löffler et al. at the Technical University of Berlin (TU Berlin) and was first published in a 2017 paper [9]. The aim was to develop a new energy system model, high in sectoral detail, and capable of modeling climate policy scenarios of a global scale. As a result, it models energy systems through coupling and interconnections of the traditionally segregated heat, power, and mobility sectors. The model endogenously determines cost-optimal paths for investment in energy generation (both conventional and renewable), storage technologies, and infrastructure. By considering emission targets such as emission budgets, the model can suggest possible cost-optimal developments towards a largely decarbonized energy system. GENeSYS-MOD is originally based on the Open-Source Energy Modeling System (OSeMOSYS), which is detailed in M. Howells et al. [80]. GENeSYS-MOD is further enhanced by including improvements such as possibilities for trade and transportation, revised global and European data, and expansions regarding emissions. [81]

3.2.1 General Model Description

The energy demands are set exogenously. To meet these, the model provides the necessary capacities by calculating the optimal flows of energy carriers and services. The illustration of GENeSYS-MOD as a flow-based optimization model can be seen in Figure 3.1. Each technology is represented as a node, and these are connected by fuels represented as arcs [81]. As can be seen in Figure 3.1, technologies can be energy generation entities such as wind, solar, or hydropower and energy conversion technologies such as storages or vehicles. The fuels connecting the technologies can be energy carriers such as electricity or fossil fuels, but they can also represent more abstract units [81]. An example of an abstract fuel unit used in the model is "passenger kilometers" which is a quantification of people's transportation needs. These transportation needs can be satisfied by, for example, personal vehicles or trains. Thus, this abstract fuel can be understood as a demand of the energy carriers electricity, hydrogen, or fossil fuels used to fuel the specific passenger transportation technology.

The fuels entering a technology can be used or transformed by the technology. The fuels exiting a technology are the products of the process within the technology. For example, the power grid delivers electricity, which is an input fuel to hydrogen production technologies. The output fuel, or product of that process, is the energy carrier hydrogen gas which is further used in other technologies. As shown in Figure 3.1, the flows of fuels end in energy demands, which are met through a combination of technologies and trade between regions. The three categories of energy demands are electricity, heating, and transportation, which are exogenously defined for each region with future projections.

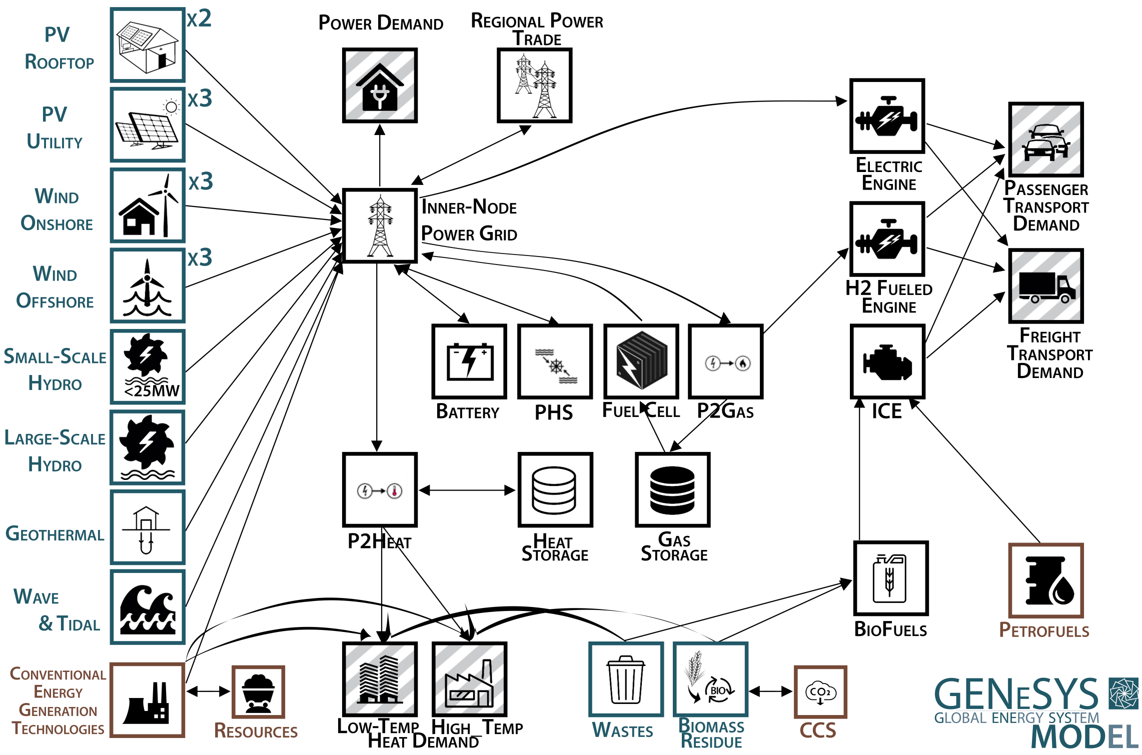

Figure 3.1: Model structure of GENeSYS-MOD v2.0 Source: Hainsch et al. [82]

A detailed description of base year specifications is also defined exogenously for each region. This includes capacities of existing power-producing and heat-producing technologies, and the energy productions of these capacities. For instance, there are specific input parameters that define the amount of heating being supplied by power, coal, biomass, etc. in the base year.

3.2.2 Previous Uses of GENeSYS-MOD

Though GENeSYS-MOD is a relatively novel energy system modeling framework, it has already been implemented in different studies. The first version of GENeSYS-MOD was used to model the global energy system as a whole [9], while later versions have modeled more specific regional areas such as Europe (version 2.0) [82] and China (version 2.1) [76]. Implementations show significant degrees of sector coupling, and that solar and onshore wind power will be important energy sources to reach the Paris Agreement decarbonization goals.

Chapter 4

openENTRANCE Scenarios

This chapter elaborates on the four openENTRANCE scenarios selected for the case study. It is described how they were developed and some of their scenario-specific features. Each scenario is therefore described qualitatively and selected quantitative demand assumptions are presented. The scenario development and the qualitative descriptions are based on work presented in the research project preceding this thesis.

4.1 Scenario Development

The four scenarios used in our work have been developed through the openENTRANCE project as described in deliverables D7.1 [2] and D3.1 [10]. The scenarios have been developed based on three key uncertainties for the energy system transition. These uncertainties are mapped using the three-dimensional storyline topology, where each axis represents one uncertainty, as seen in Figure 4.1. Close to the center of the coordinate system, the exposure of each uncertainty is low. The farther away from the center, the higher the exposure of the respective uncertainty. The three key uncertainties identified here are (1) geopolitical and economic development, (2) novelty and availability of technologies, and (3) society's attitude and lifestyle. [2]

Geopolitical and economic development represents uncertainties related to future degrees of global prosperity and peaceful geopolitical relationships. Uneven wealth distribution, geopolitical tensions, and trade conflicts can be considered the opposite extreme. These might challenge the current openness of trade and are factors that would disrupt the future energy world. [2]

Novelty and availability of technologies represents uncertainties related to technological advancements and innovations. Examples of technologies that are not commercially available or economically feasible today, but might be in the future, are floating offshore wind turbines, hydrogen production from renewable sources, and CCS. [2]

Society's attitude and lifestyle represents uncertainties related to communities' willingness to adapt to and support the low-carbon energy transition. There is a high level of uncertainty related to this because even though it may seem like society is voicing strong opinions towards a low-carbon energy system, there is historically a large gap between people's intentions for a sustainable lifestyle and reality. [2]

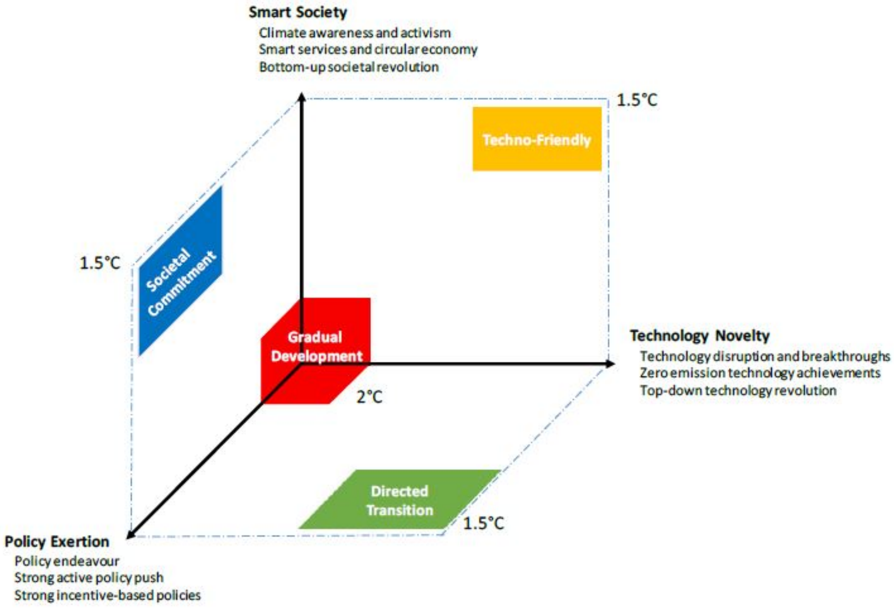

Figure 4.1: Illustration of the scenario dimensions. Source: openENTRANCE [2]

The three most ambitious scenarios are defined by the combination of two sets of key drivers in the energy transition. Each driver is the positive outcome of one of the respective uncertainties: policy exertion, technological novelty, and smart society. Meanwhile, the fourth scenario can be considered a more conservative scenario, with "a little bit of everything", but no favored drivers. Figure 4.1 illustrates the three main drivers and how their positive aspects shape the scenario dimensions. [2]

Although the scenarios are defined by different key uncertainties, several common features are present in all of them. These features include high shares of renewable energy sources in the European energy system, considerable levels of demand-side participation by individuals and communities, and an ambitious target of limiting global warming to 1.5°C compared to pre-industrial levels. The exception is the Gradual Development scenario, where the target is 2°C. Further similarities between the scenarios targeting 1.5°C include high carbon pricing and strong exploitation of digitalization potentials. It is worth noting that all scenarios are uncertain and neither of them is regarded as significantly more probable than the others in the openENTRANCE project. [2]

4.2 Scenario Descriptions

4.2.1 Societal Commitment

General Scenario Description

This scenario is characterized by a revolution of mindsets in societies where awareness and engagement related to the importance of reducing one's carbon footprint becomes widespread. This revolution ranges from a bottom-up level where individuals take measures to reduce their consumption to a top-down level where comprehensive policies towards societal decarbonization are put into law, highly backed by the population. The sum of the implemented measures in the scenario results in reaching the 1.5°C target, despite assuming that there will not be any major technological developments or breakthroughs. [2]

What makes this scenario unique is the extent to which society is willing to adapt to a greener lifestyle. This adaptation includes widespread implementations of circular and sharing economies, willingness to pay/invest extra for goods and services and openness to take part in projects to unlock demand-side flexibilities. Additionally, it is assumed that completely new green market solutions and business models will emerge, with the help of policies specially designed to support them.

The Societal Commitment scenario assumes a uniquely large decrease in energy demand across all energy sectors due to the efforts made across societies to reduce environmental impacts. This decrease in energy demand is especially significant in the transport sector because the sector is particularly dependent on social trends. For example, if most people stop commuting by car but instead use bikes or public transport, then less energy would be needed in the transport sector. Also, with less demand for products, there is less energy needed for freight transportation. Residential heating is the only sector where Societal Commitment does not assume the lowest energy demand of the four scenarios. [10]

Societal Commitment is similar to the Techno-Friendly scenario in that both assume a high demand for solutions that can contribute to emission reductions, which can be considered a market pull. Unlike the Techno-Friendly scenario, new green solutions are strongly supported by policy, partly because there is a lack of major technological advancements in the power and transport sectors (not counting digitalization technology), making the solutions profitable without support. The impact of dedicated policies towards cutting emissions is also found in the Directed Transition scenario. However, the Directed Transition policies are mostly directed towards implementations of new technologies, while policies in the Societal Commitment scenario focus on supporting green initiatives for reducing consumption. [2]

Quantitative Scenario Description

The Societal Commitment scenario has the highest 2050 CO_2 penalty with a cost of 1275 € /ton CO_2 emissions (see Figure 4.2). It is also the only scenario where no new nuclear can be built in any regions, no CCS or Direct Air Capture (DAC) can be utilized, and the use of hydrogen is very limited. However, the fixed costs for PV on rooftops are about one-third of the costs in the other scenarios, and their capacity factor is higher, making them especially cost-efficient in this scenario.

4.2.2 Techno-Friendly

General Scenario Description

Instead of communities having positive societal attitudes regarding reductions in emissions manifesting into green policies like the Societal Commitment scenario, these attitudes are instead expressed by the extensive willingness to adopt new technologies and large-scale infrastructure projects. The lack of centralized policies means that it is the market that drives the implementation of new technologies. Examples of market participants range from individuals seeking a greener lifestyle to industries working to accommodate the demand for environmentally friendly solutions. [2]

What makes the Techno-Friendly scenario unique is the assumption that technologies like floating offshore wind, hydrogen production, and CCS will be economically viable

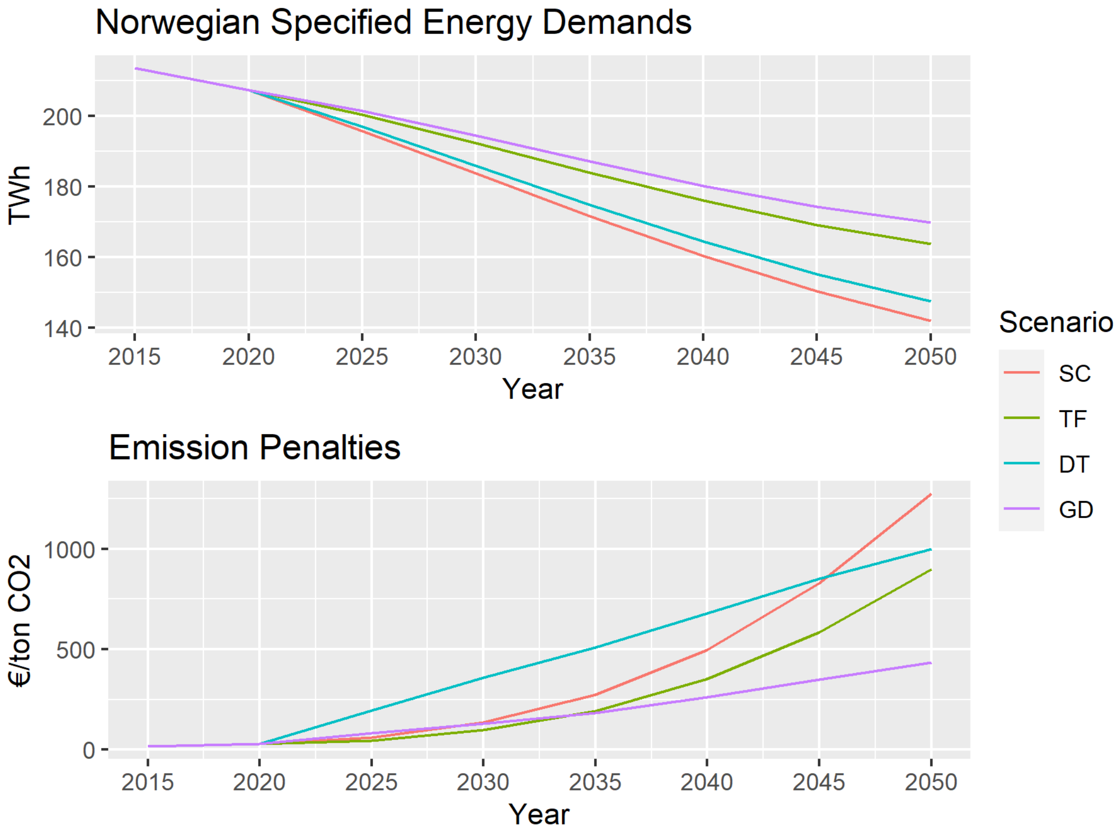

Figure 4.2: The GENeSYS-MOD input values for the parameters *EmissionPenalties* and the combined Norwegian *SpecifiedAnnualDemand* for heat and power.

to implement on a large scale to meet the demands for energy and transport services. The scenario shares some similarities with Directed Transition because both feature the widespread use of new technologies. However, a key difference in the Techno-Friendly scenario is that the market forces are the main drivers for technology implementations, not policymakers.

The Techno-Friendly scenario features the second-highest power demand and shares the highest energy demands in the transport and heating sector with Gradual Development. The reason why the energy demand can remain comparatively high in the Techno-Friendly scenario is that it assumes that most of the demand can be supplied by emerging green technologies while reaching the target of 1.5 °C. [10]

Quantitative Scenario Description

The Techno-Friendly scenario contains the second-lowest CO_2 penalties with a 2050 penalty of 900 € /ton CO_2. It is the only scenario where road-powered electric vehicles can be used for road freight transportation, and this technology can supply up to 50% of this transport demand. The capacity factor for offshore wind is also higher than those in the Societal Commitment and Gradual Development scenarios. Also, it is the only scenario that enables the import of hydrogen from regions that not are represented as individual nodes in the model, like China and Russia.

4.2.3 Directed Transition

General Scenario Description

Like the Techno-Friendly scenario, there are significant developments in technologies that can reduce carbon emissions in the Directed Transition scenario. However, they are not regarded as economical and receive minimal support from a society that is less willing to reduce their consumption. New technologies related to low-carbon energy services are therefore implemented with the support of incentives provided by the public sector. Additionally, direct partnerships between policymakers and industry and technology developers emerge to facilitate broad advances in low-carbon energy-related technologies. [2]

The Directed Transition Scenario contains the second-lowest energy demands of the four scenarios described [10]. The main reason for this relatively low demand is that policies are put in place to encourage the widespread use of heat pumps, which can provide heat with less energy use than combustion-based systems or electric heaters. Gradual Development shares the same transport sector demands [10]. These energy demands across all sectors are generally assumed to be comparatively low despite the minimal societal effort to counteract climate change, because of the policies put in place to limit global warming.

What sets this scenario apart from the others is that the policymakers are the main driving forces behind the implementation of new technologies in the power and transport sectors. At the same time, the overall population refuses to take serious steps to reduce their carbon footprints. Industries are therefore dependent on continuous backing from technology-specific public policies. However, this support allows the industries to deliver emission reduction technologies which are used to a sufficient extent to reach the target of 1.5 °C. [2]

Quantitative Scenario Description

The Directed Transition scenario contains the highest CO_2 penalties overall and has the second-highest 2050 penalty of 1000 € /ton CO_2. It is the only scenario without fixed limits for nuclear power. It also features the most favorable capacity factors for offshore wind, compared to the other scenarios.

4.2.4 Gradual Development

General Scenario Description

This scenario assumes an equal contribution among societal behavior, technological development, and policy action. This moderate combination of all three dimensions is what distinguishes Gradual Development and allows it to serve as a reference scenario in openENTRANCE. While being less ambitious than the other scenarios, it still features significantly higher efforts towards decarbonization than a continuation of current policies to limit global warming to 2°C. [2]

The Gradual Development Scenario assumes the largest power demands and shares the highest energy demand in the transport and heating sector with the Techno-Friendly scenario. These demands are partly a result of a less ambitious climate goal than the other scenarios.

Quantitative Scenario Description

Gradual Development naturally features the lowest emission penalties with less ambitious climate goals than the other scenarios, which reach 435 €/ton CO_2 in 2050. The scenario relies heavily on existing technologies. As such, novel technologies such as hydrogen, CCS, and DAC are disabled. Figure 4.2 shows how the Gradual Development scenario demands more energy in Norway while allowing for higher CO_2 emissions than the other scenarios.

Chapter 5

Model Verification, Validation, and Modification Process

This chapter explains the methods conducted for this thesis. First, it presents the efforts that were made to ensure that the results generated from running GENeSYS-MOD independently were the same as the results produced by openENTRANCE (model verification). It is described how data from GENeSYS-MOD was compared with statistics and projections from reliable sources (model validation). Finally, the improvements made to the scenario input data are presented.

5.1 Model Verification

The verification process is conducted on GENeSYS-MOD version 3.0. This version was publicly released at the end of 2020, along with a sample dataset ready to run with the model's default settings [83].

Results from running the model with the Gurobi solver were quite similar to the results received from openENTRANCE. The objective values, for example, were identical for each scenario. However, there were still some differences, for example in the offshore wind sector, as illustrated in Figure A.1 in the appendix. After discussing these findings with the GENeSYS-MOD developers, it was concluded that the optimization problem solved by the model had an infinite number of optimal solutions, as different solutions resulted in the same objective value. It was also discussed that a property of linear programs is that they either have zero, one, or an infinite number of optimal solutions. Unfortunately, having an infinite number of optimal solutions can make it difficult to reproduce results. The developers, therefore, decided to adjust the costs for different offshore wind technologies, to cut down the number of optimal solutions.

Results generated after these adjustments also had the same objective values as the results received from openENTRANCE. However, when analyzing the results in detail, many numerical differences were discovered between corresponding technologies in the generated and received results. For instance, technologies were producing in different time slices, and in the Societal Commitment scenario, there were differences in which PV technologies that were prioritized, see Figure A.2 in the appendix. This can be expected if there are infinite optimal solutions to the model because the solution path found by Gurobi can be highly dependent on hardware [84]. If the GENeSYS-MOD results are to be completely reproduced, its code and input data should be updated such that the model features minimal differences in its optimal solutions, especially when it comes to deployment of new technologies. It is therefore necessary to ensure that fuels and technologies have different cost and efficiently related constants to make them mathematically distinct. However, because the generated results feature the same objective values, as well as the same total capacities and productions as the received results, GENeSYS-MOD is considered to be sufficiently verified for the analyses presented in this thesis.

5.2 Model Validation

GENeSYS-MOD aims to find a cost-minimizing optimal solution to supply given energy system demands. It can be used for finding low-emission solutions, and is not aimed at predicting how systems will develop. However, it is crucial that the scenarios modeled by GENeSYS-MOD are based on historically correct starting points. Therefore, a significant part of this thesis' work has been to analyze the scenarios' base year (2015) values to see how well they match historical values.

The Norwegian power capacity, power production, and power consumption have been among the main parameters and variables analyzed for this thesis because they are key aspects of the Norwegian energy system. Historical annual statistics for these are available from the Norwegian Bureau of Statistics (SSB) [85, 86], and their future developments are of high interest to the modeling community, policy makers, and industry stakeholders in Norway.

Values produced by GENeSYS-MOD for Norwegian power capacities, productions, and balance are compared with results from the long-term power market analyses published in October 2020 by the Transmission System Operator (TSO) Statnett [64] and NVE [11]. Statnett's report presents an analysis of the power market from 2020 to 2050 and provides values for every decade. NVE's report models the years 2020 to 2040, and provides values for every fifth year, except for the year 2035. In the comparisons with the GENeSYS-MOD results, interpolation is used to estimate the values that were not provided in the reports. Assuming that NVE and Statnett have access to more accurate data related to the current power sector than openENTRANCE, and more experience with historical Norwegian power sector developments, the results of the reports can be used as baselines for probable Norwegian power system developments to validate and evaluate the GENeSYS-MOD results.

Another part of the validation effort was to analyze the input data of GENeSYS-MOD. During these analyses, several model and input data shortcomings were discovered. The following section describes these issues and explores modifications that can be made to the input data, while the results section presents the effects of these modifications.

5.3 Modifications Made to GENeSYS-MOD

5.3.1 Hydropower

GENeSYS-MOD features the parameter *AvailabilityFactor*, which describes the maximum time a technology can be considered to run at full capacity during given years in each region. The availability factors of all technologies are based on values specified for Germany. For larger hydro installations, the availability factor was originally set equal to 0.33, which is significantly less than the factor of 0.48 that can be calculated from NVE's data [87]. Furthermore, a notable limitation of GENeSYS-MOD is that there is no functionality to account for retrofitting of hydro plants. Consequently, the model reports constant or decreasing values for Norwegian hydro capacity and production. This contrasts with projections made by NVE, which expects hydropower installations to increase in the coming years [11]. A possible workaround for this issue is to increase the availability factor for hydropower for future years in the model. While this solution would not change the hydro capacities reported by the model, it would increase the available hydro production, which would reduce the demand for other energy sources.

Updated availability factors of the large hydro capacities were calculated based on the hydro productions projected by NVE, using formula 5.1. NVE's projections are shown in Table A.2 in the appendix. The resulting values are shown in Table B.7 in the appendix.

$$A_y = \frac{cP_y - dS}{L} \qquad \forall y \in \{2015, 2020, ..., 2050\} \tag{5.1}$$

where:

A_y = The new availability factor in year y
c = $\frac{1}{8.760h}$ = The conversion factor between annual TWh and GW
P_y = Total hydro production in year y, modeled by NVE
d = The default availability factor for small hydro in GENeSYS-MOD
S = The default value for Norwegian installed small hydro capacity across all years
L = The default value for Norwegian installed large hydro capacity across all years

5.3.2 Trade Costs

The developers of GENeSYS-MOD added trade costs for hard coal, biomass, oil, hydrogen, and power, calculated based on the trade distances between regions, after it was discovered that trade costs were missing. This has improved the trading between the countries. However, several fuels were still missing trade costs. These fuels included biofuel, liquefied hydrogen (LH2), and liquefied natural gas (LNG). To fix this issue, trade costs were added for these fuels using the same assumptions as those used to calculate oil and hydrogen trade. This can be justified because the trade cost calculations for liquid and gaseous fuels in openENTRANCE are based on truck transport over the specified trade distance.

5.3.3 Specified Annual Demand

Industrial Heating Sources The industrial sector in GENeSYS-MOD is defined by supplying three demands for heating, defined by temperature ranges. These are low temperature (<100°C), medium temperature (100-1000°C), and high temperature (>1000°C) industrial heating (HLI, HMI, and HHI, respectively). To determine the industrial heating demands, openENTRANCE used the European Commission's 2017 mapping of heating fuel deployment [88], combined with a research article quantifying the European industrial heat demand [89]. For Norway, these assumptions posed several challenges, which will be further discussed in Chapter 8. One of these was that the research article only studied European Union (EU) countries, so Norway was not included. Another challenge was that in the disaggregation of Scandinavia, these sources appear to be used in a different way than they were for determining the initial model data.

Industrial Heating Allocation The total industrial heating demand of 66 TWh was equal to the statistical total industrial energy demand in 2015 [90]. As there are currently no defined openENTRANCE parameters to include other industrial demands than heating, the total industrial heating demand was not modified. However, the demand distribution between HLI, HMI, and HHI was not correct. This could easily be seen by comparing the defined HLI demand (6.6 TWh) with the 2018 industrial low temperature heating demand from NVE (35 TWh) [28]. For this reason, the input demand for HLI was updated to 35 TWh. For the sum to remain unaltered, the HHI demand was decreased to 24.4 TWh, while the HMI demand was kept at 6.6 TWh. Of the 35 TWh demand for HLI, 18 TWh are supplied by power [28]. Little industrial heating was originally supplied by power in the model, so a regional base year production of 18 TWh and a base year residual capacity of 2 GW for direct electric HLI were added.

Residential Heating The residential heating (HLR) demands had also been defined using the European Commission's mapping of heat fuel deployment [88]. The defined base year demand could be validated using NVE's 2018 low temperature heating source [28]. However, similarly as for industrial heating, it could be seen that none of this was supplied by electricity. About 80% of residential heating was supplied by direct electricity in 2018 [28]. Therefore, a regional base year production for Norway of 30.4 TWh and a base year residual capacity of 3.5 GW for direct electric HLR were added as input parameters.

Power Demand The power demands in the model are not determined explicitly from a single source. Rather, they are determined based on power production and power consumption in industries and residences. The base year power production used was 145 TWh, which could be validated with statistics for the Norwegian power production in 2015 [90]. To get the final base year power demand in GENeSYS-MOD, we could calculate:

$$
\begin{aligned}
\text{Specified power demand} &= \text{Total power production} \\
&\quad - \text{Power for residential heating} \\
&\quad - \text{Power for industrial heating} \\[1em]
\text{Total power production} &= 145 \text{ TWh [90]} \\[1em]
\text{Power for residential heating} &= 0.8 \text{ x Total energy for residential heating} \\
&= 0.8 \text{ x } 38 = 30.4 \text{ TWh} \\[1em]
\text{Power for industrial heating } (<100^\circ\text{C}) &= 0.65 \text{ x } 16 + 0.4 \text{ x } 19 = 18 \text{ TWh [28]} \\[1em]
\Rightarrow \textbf{Specified power demand (base year)} &= 145 \text{ TWh} - 30 \text{ TWh} - 18 \text{ TWh} = \textbf{97 TWh}
\end{aligned}
$$

The specified annual power demand was hence updated to 97 TWh, which is 13 TWh lower than what was previously determined.

5.3.4 Additional Improved Parameters

Following is a description of additional parameters that were updated for the model run in this thesis. These parameters were observed to have incorrect values in the original dataset and have been updated using reliable sources.

Power Trade

The Net Transfer Capacities (NTC) were updated based on the map in Figure B.1 in the appendix which has been developed based on the European Network of Transmission System Operators for Electricity (ENTSO-E) transparency platform [91]. In addition, as the North Sea Link line to the UK is under construction and will be operating within the near future, this was also added with a trade capacity of 1.4 GW [27]. An additional 1.4 GW trade capacity was added to the UK to account for the planned construction of the North Connect line, which may be realized in 2024 [92]. This transmission line is more uncertain but is added due to its presence in ENTSO-E's TYNDP 2020 national trend scenario until 2025 [93].

Natural Gas Trade

Input gas trade capacities were updated with values from Gassco [94], resulting in slightly lower gas trade capacities. The pipeline to the Netherlands was removed from the original input data, as it does not exist.

Oil and Gas Resources

The oil and gas resources for Norway were underestimated due to a disaggregation of Scandinavia into the regions Norway, Sweden, and Finland. Equal oil and gas resources were given to each country, while they should have all been allocated to Norway. This was fixed in the model by removing these resources from Sweden and Finland. Improved values were calculated using data from the Norwegian Petroleum Directorate (NPD) [95]. From these values, the amount of resources already sold were subtracted, as well as the amount of undiscovered resources.

CCS Potential

An updated value for Carbon Capture and Storage (CCS) potential was found from the NPD [96]. This new total value for CCS potential is 4 times higher than the original input value.

Hydropower Residual Capacity

The residual capacity for several technologies is defined in the input data as the capacity left over from periods prior to the modeling period. The total hydropower residual capacity was approximately correct, but the allocation between dispatchable hydro and run-of-river hydro was wrong. GENeSYS-MOD categorizes all hydro smaller than 10 MW as run-of-river, and all other hydro as dispatchable. However, this does not accurately depict the Norwegian hydropower conditions. Using the hydropower data from the TIMES model, the allocation of dispatchable and run-of-river hydropower capacities was improved.

5.4 Visualizing the Results

GENeSYS-MOD outputs a vast amount of country-specific data for 35 years, featuring over a hundred different technologies. Significant efforts have therefore been made to create detailed and comprehensive visualizations of key model results. Parts of these efforts have focused on creating interactive maps that display how the total installed capacities or total power production of different technologies in different countries develop in Europe. Figure 5.1 shows the layout of these maps, which have been attached to this thesis' submission. Note that an internet connection is required to open them. For simplicity, countries aggregated into the "NONEU_Balkan" node in GENeSYS-MOD are not included, resulting in some Balkan countries missing. The maps can temporarily be found at `https://folk.ntnu.no/akselhso/GeneratedMaps/` in the folders "OriginalResults/", "ImprovedResults" and "DisaggregatedResults/"

The color code of each region visualizes the share of power production or power capacity from renewable sources. The specific values for each region can be viewed by hovering over or clicking on the respective region. The maps also contain a slider used to specify the year of the illustrated data. By clicking on the play button, the map will show GENeSYS-MOD's modeled values for future years. The animation will show countries becoming greener over time, indicating that their power systems become increasingly made up of renewable energy sources.

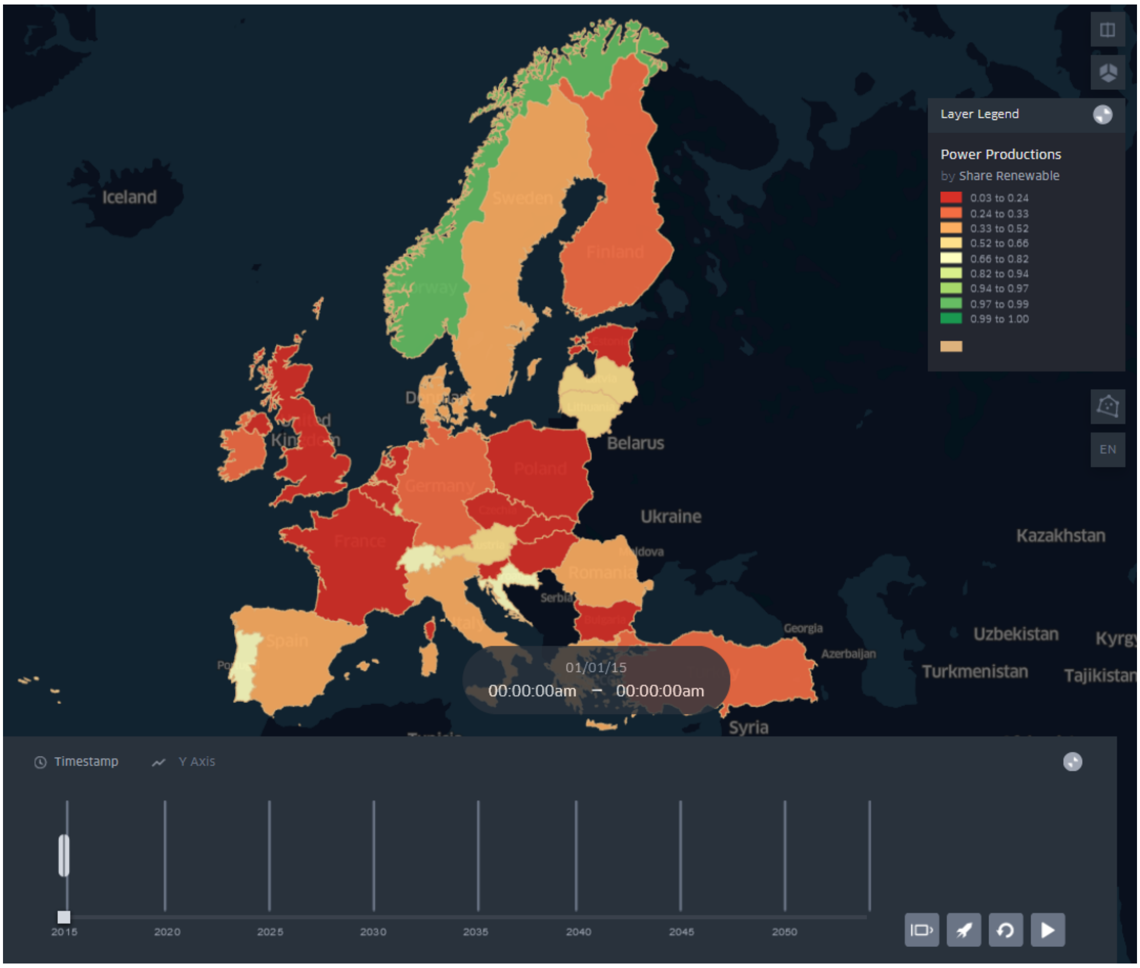

Figure 5.1: Image of an interactive map of a GENeSYS-MOD scenario

Chapter 6

Case Study: Disaggregating Norway

This chapter describes the process used to disaggregate Norway into five new regions. To either add new regions, or disaggregate existing regions in GENeSYS-MOD, several parameters must be updated in the input dataset. These include demands for power, heating, and transportation, base year productions and capacities, and availability of resources. Regional hourly profiles for weather parameters such as solar irradiance and reservoir inflow must be included, in addition to hourly profiles for power, heating, and transportation demands. The process of disaggregating these parameters is presented in this chapter, including challenges that were encountered and observations made.

6.1 Initial Disaggregation Process

As the user guide for disaggregating an existing region was lacking, the process of disaggregating Norway into five new regions became a lengthy trial-and-error process. For the initial model runs, the goal was to successfully add five regions, and to disaggregate the regional data by equally splitting the parameters.

The initial data disaggregation was done in a two-step process. First, the five new regions were added, each an identical copy of the original aggregated Norwegian region. Secondly, the data for each region was disaggregated by splitting demand, capacity, and base year production parameters by five.

6.2 Final Disaggregation Process

After testing the model with equally disaggregated data, the dataset could be modified to represent regional conditions. The distribution of various factors was determined. These are seen in Table 6.1 and included population, location of large industry, and land area. In NVE's report [97] a similar distribution is used to disaggregate country-level data for Norway into the five bidding zones. NVE argues that the population shares can be used to disaggregate parameters dependent on building area, such as residential heating and power demand, and that the same shares can be used to disaggregate transportation parameters, such as mobility demand. This argumentation was justified by the lack of good statistics available for location of buildings and transportation in Norway at the time [97]. The industry shares are based on statistics for how much energy the largest companies use and which counties they are located in [97].

Table 6.1: Regional shares 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%

Similar assumptions as those used in NVE's report were used to disaggregate most of the parameters. Power, mobility, and residential heating demands were disaggregated based on population. Industrial heating demands were disaggregated based on the location of large industries. Base year production and capacity parameters relating to residential heating were disaggregated based on population, while those relating to industrial heating were disaggregated based on the location of industry. Parameters relating to resources and resource potentials were disaggregated based on land area.

Power trade capacity values between the regions were updated with the actual NTCs, as seen in Figure B.1 in the appendix. The trade routes were also updated with more realistic distances, measured in kilometers between the approximate geographic centers of each region.

Regional onshore wind potentials were updated based on a figure in SINTEF's energy roadmap [98]. The potentials in SINTEF's report are based on the locations of current and future onshore wind projects. In addition, factors such as wind conditions and geographical terrain have impacted these potentials.

Oil and gas resources were disaggregated using data from the NPD for resource allocation in each sea on the Norwegian coast [95]. It was assumed that there are no resources in NO1, that the Barents Sea resources are in NO4, that the Norwegian Sea resources are in NO3, and that the North Sea resources are split evenly between NO2 and NO5. Similarly, the CCS potentials were disaggregated using data from the NPD [96].

Offshore wind production was removed from NO1, as there is no offshore wind potential in that region. New regional wind and solar data was collected using `renewables.ninja`. However, a closer inspection of the results showed unrealistically high power production in certain regions. Inspection of the new input data showed inconsistencies compared with data used for the other regions. Thus, the use of the original onshore wind and PV hourly data was continued for all regions.

6.3 Observations

An observation made was that GENeSYS-MOD is sensitive for small errors in the base year input parameters. It can be mitigated by disabling the base year specifications. This will relax several constraints and make it easier to identify the problems.

When disaggregating data, it is important to consider the parameter type, to ensure to not disaggregate e.g., a fractional parameter. Apart from being conceptionally wrong, it will cause modeling issues.

Demands, base year production, and capacities for relating fuel types and technologies must be disaggregated using the same assumptions, i.e., the demand for low temperature residential heating (HLR) must be disaggregated in the same way as the residual capacities and regional base year productions for HLR technologies. Similarly, industrial heating demand disaggregation must correspond to capacity and production disaggregation for HLI, HMI, and HHI (heat low, medium, and high industrial, respectively) technologies. In our case, all residential heating parameters were disaggregated based on population, and all industrial heating parameters were disaggregated based on location of industry.

Importance of Temporal Resolution

The temporal resolution can be chosen by the user. In the GENeSYS-MOD source code, suggestions for which resolution to choose are commented. The highest suggested resolution is to model one hour every 73 hours, which results in 120 yearly time slices. The lowest suggested resolution is to model one hour every 1000 hours, which results in 8 yearly time slices.

For time-saving purposes in the implementation phase, it was useful to run the scenarios with the lowest time resolution. However, it is important to be aware that this greatly affects variable renewable energy sources such as wind and PV and thus a proper analysis of the results cannot be done. For instance, when running the model with a lower temporal resolution, significantly more solar power was produced compared to the high-resolution run. The model run with a higher resolution will represent the discrepancies over day and night better, and thus implement PV more realistically. This is due to the time-clustering algorithm used to better represent the storages. This is further explained in the dynELMOD data documentation [99].

Chapter 7

Results and Analysis

Three sets of results will be presented in this chapter. Firstly, results generated from the most updated dataset and model version received from openENTRANCE will be analyzed. These results will be referred to as the "original" or "orig" results. Secondly, results generated from input data with improved Norwegian values are presented along with an analysis of the effects of the input modifications and a discussion of the validity of the results. The results from these modifications will be referred to as the "improved" results. Finally, results generated from the disaggregation of Norway into the country's five bidding zones are presented, and the regional differences and possible future developments are analyzed. These results will be referred to as the "disaggregated" results. The four openENTRANCE scenarios Directed Transition, Techno-Friendly, Societal Commitment and Gradual Development will be abbreviated to DT, TF, SC, and GD, respectively, in the following sections.

7.1 Original Scenario Results

7.1.1 Power Capacities and Production

The total Norwegian capacities generated from the original input data are shown in Figure 7.1. It shows how hydropower initially makes up most of the capacities. However, the model quickly prioritizes onshore wind developments, which reach peak capacity in 2030 for all scenarios, while the hydro capacities remain stable. In 2035, DT and SC reach their peak offshore wind capacities. GD reaches its peak in 2040, while TF gradually increases its offshore capacity between 2040 and 2050. There are also developments in solar power capacities after 2030, especially in the SC scenario.

The total Norwegian power productions are shown in Figure 7.2. These correlate to the total capacities, but also depend on the availability and capacity factors of the technologies. While the SC scenario has the highest total capacity, it does not produce the most power. This is because PV, which has a lower capacity factor than wind plants, accounts for a larger share of the SC power system than in the other scenarios.

7.1.2 Power Balance

The net Norwegian exports are shown in Table 7.1. The full power balance is plotted in Figure A.3 in the appendix. The table shows that GENeSYS-MOD initially models Norway to be a net

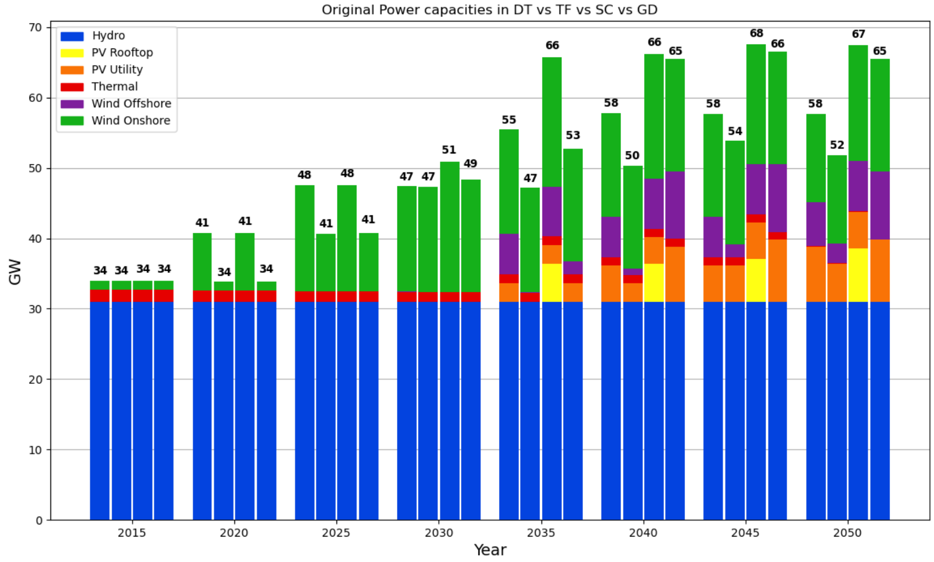

Figure 7.1: Norwegian power capacities in the original scenarios

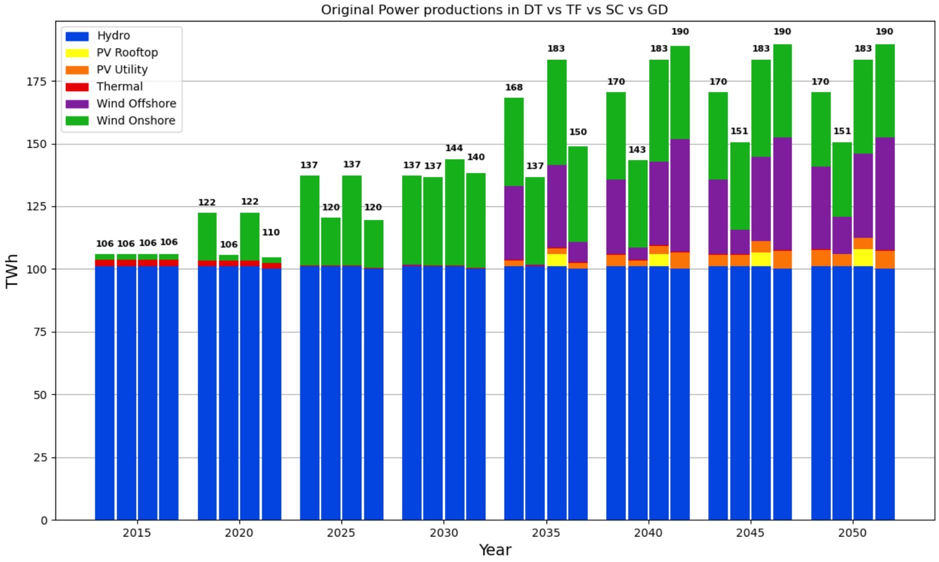

Figure 7.2: Norwegian power productions in the original scenarios

importer of power in the base year, which was not the case in reality. It also shows that Norway in the 1.5°C scenarios quickly becomes a net exporter because the country increases its power production faster than its consumption. Contrarily, in the GD scenario, Norway remains a net importer until 2035, before offshore wind developments take off.

For further inspection of the original power capacity and production results, interactive maps can be found in the attachments or at: `https://folk.ntnu.no/akselhso/GeneratedMaps/`

`OriginalResults/`

Table 7.1: Net power exports [TWh] in the original scenarios

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
DT	-6.8	4.0	9.9	2.5	25	3.8	0.83	0.87
TF	-6.8	-9.3	5.0	15	15	22	5.4	3.5
SC	-6.8	4.0	13	20	10	11	13	20
GD	-6.8	-12	-4.0	-26	-23	14	18	22

7.2 Impacts of Improved Input Data

Figure 7.3 shows the Norwegian power productions for all scenarios generated from the improved input data. Substantially more hydropower is produced, due to higher availability factors. The additional available hydropower also limits the need for other energy sources. While the onshore wind developments are initially quite similar to the original results, the developments plateau in all scenarios at 35 TWh in 2030 instead of growing to 42 and 38 TWh like in the original SC and GD results. The corresponding power capacities are shown in Figure A.5 in the appendix.

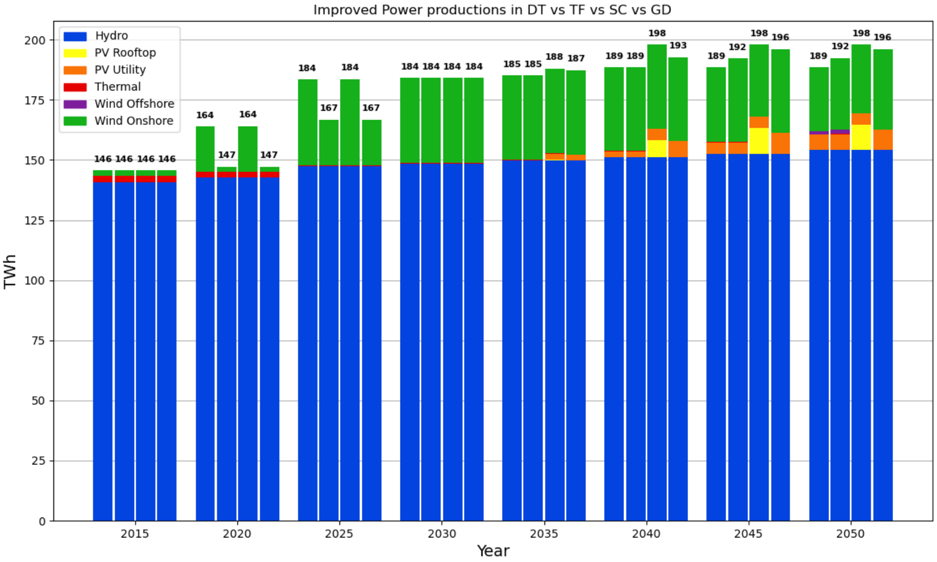

Figure 7.3: Norwegian power productions in the improved scenarios

Offshore wind developments are minimal in the improved scenarios. This is primarily because the power demand is already supplied by other energy sources, which produce significant amounts of surplus power. The improved net exports, listed in Table 7.2, are significantly higher than original numbers, which does not make it profitable to export offshore wind power. The full power balance is shown in Figure A.6 in the appendix.

On the other hand, PV capacities are generally utilized more in the improved scenarios than in the original ones. One reason for this is that the power consumption in the improved scenarios

Table 7.2: Net power exports [TWh] in the improved scenarios

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
DT	2.4	16	33	30	26	23	21	16
TF	2.6	3.1	26	47	52	29	28	23
SC	2.5	4.7	30	21	22	38	29	30
GD	2.6	4.1	20	24	25	32	40	18

increases more than in the original scenarios after 2035, due to increased hydrogen production. In 2050, PV makes up between 14% and 27% of the installed capacities depending on the scenario, as illustrated in Figure A.5 in the appendix. However, PV only makes up between 4% and 8% of the total power production, due to its low capacity factor.

The scenarios contain significant variations in the installed capacities and productions for the modeled years. SC and DT assume high political willingness to implement decarbonizing policies; therefore, they can heavily invest in existing technologies that are not yet cost-efficient. This is partly the reason why these scenarios feature a rapid expansion of onshore wind that results in relatively high power exports in 2020. SC is also the only scenario with investments in rooftop PV capacities because it assumes a high willingness among the population to invest in environmentally friendly technologies.

Although the TF scenario contains the most favorable cost- and efficiency-related conditions for the development of offshore wind technologies, it is originally the scenario that utilizes offshore wind the least. This is primarily because this scenario also assumes the highest increases in technology efficiencies, reducing the energy demand. Offshore wind power production is generally the most expensive renewable power-producing technology. Lower power consumption will result in less offshore wind development and cause the total capacity and production values in TF to be lower than the other scenarios. However, it can be seen in the improved results that some offshore wind is used in TF in 2050, even though the onshore potential is not fully exploited. This suggests that offshore wind could eventually become more cost-efficient than onshore wind in some instances.

Another consequence of more available power is that is causes the power price to drop, which makes hydrogen production more suitable in Norway (see Figure 7.4). The orig and improved hydrogen balances for all scenarios are shown in Figures A.4 and A.7 in the appendix. Figure 7.4 also shows how the volume of traded hydrogen is much smaller after trade costs were added for liquefied hydrogen, and that most of the produced hydrogen is exported in 2050.

The effects of adding power-consuming technologies to the residential and industrial sectors are not shown here but rather in Figures A.8 and A.9 in the appendix. With the improved dataset, the key takeaways are that GENeSYS-MOD models power to supply a larger share of the energy demands in these sectors, which corresponds better with power consumption statistics for these sectors.

For further inspection of the improved power capacity and production results, interactive maps can be found in the attachments or at: `https://folk.ntnu.no/akselhso/GeneratedMaps/ImprovedResults/`

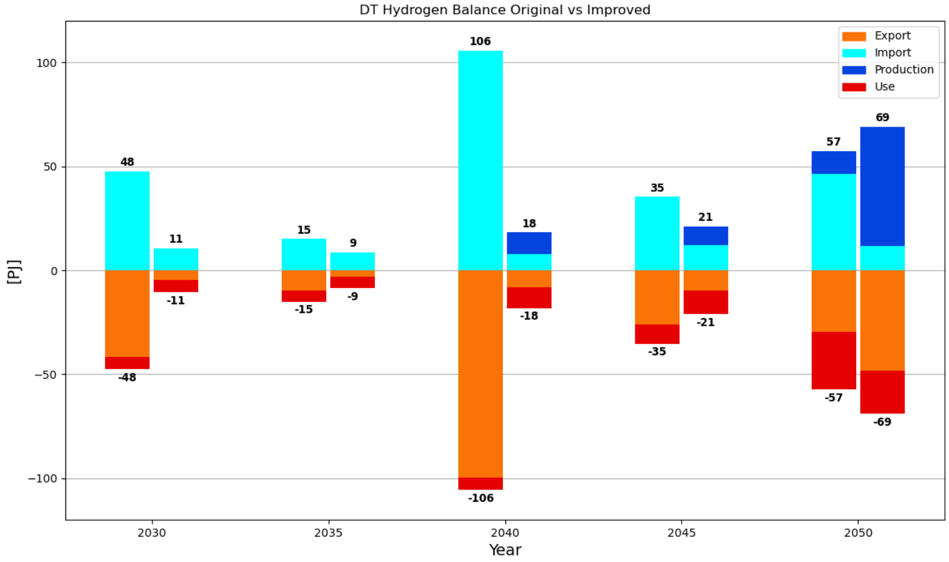

Figure 7.4: Norwegian hydrogen balance [PJ] in the original and improved DT scenarios

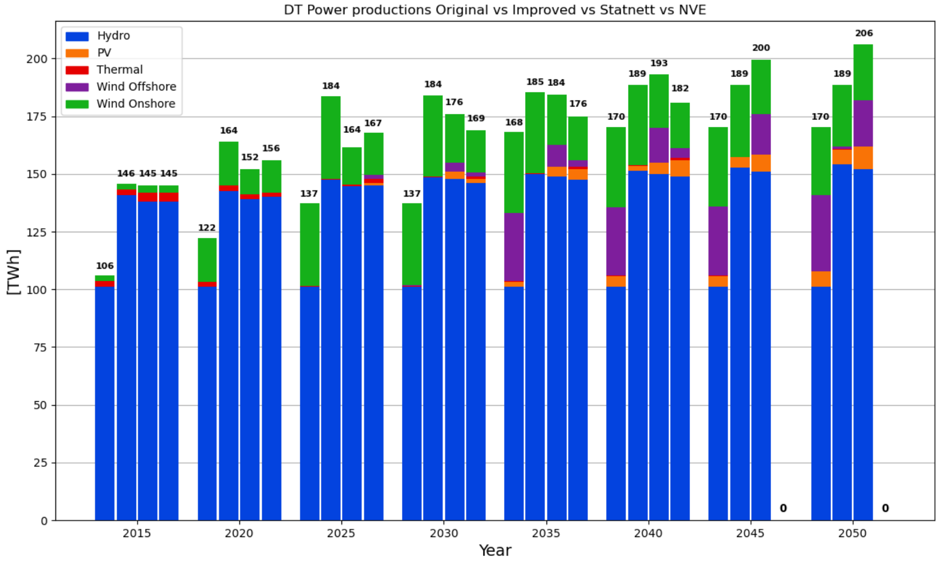

Figure 7.5: Norwegian power productions in the original and improved DT scenarios, compared with studies from Statnett and NVE [11, 64]

7.3 Model Validation and Comparison

Figure 7.5 shows how the orig and improved scenarios compare with the 2020 long-term market analyses from Statnett and NVE in terms of total power production. The available corresponding capacities are shown in Figure A.10 in the appendix. Note that NVE's analysis does not include 2045 and 2050. The base year production in the improved results is much more similar to 2015 statistics than originally. The GENeSYS-MOD results are quite optimistic regarding onshore wind power developments compared to NVE and Statnett. The original and improved DT scenario results both show 19 TWh of onshore wind power production in 2020, while Statnett and NVE project 11 and 14 TWh, respectively. The actual wind power production in 2020 was almost 10 TWh [17], meaning that all four models have overestimated the wind power production.

The results after 2020 are not directly comparable because the assumptions are different between the openENTRANCE scenarios and the two long-term market analyses. However, it is still interesting to observe the range of possible developments depicted by the differences in the Statnett and NVE results, because they illustrate how different assumptions can impact the end results. Statnett and NVE try to estimate how the energy system will most likely develop. The openENTRANCE scenarios, on the other hand, are for finding the lowest-cost solutions for reaching the 1.5°C or 2°C targets.

The improved results contain the highest power productions among the results in the early years. However, Statnett assumes a high degree of electrification and more industry development than the DT scenario. Thus, Statnett assumes higher demand for power after 2020, which causes it to have the highest production, partly supplied by offshore wind. NVE's analysis is more conservative than Statnett's in its assumptions regarding power consumption in industries, and offshore wind developments. Consistently, NVE projects lower production than the improved DT scenario. This range between NVE's and Statnett's analyses indicates that the total production modeled by GENeSYS-MOD could be reasonable for the latter half of the modeling period.

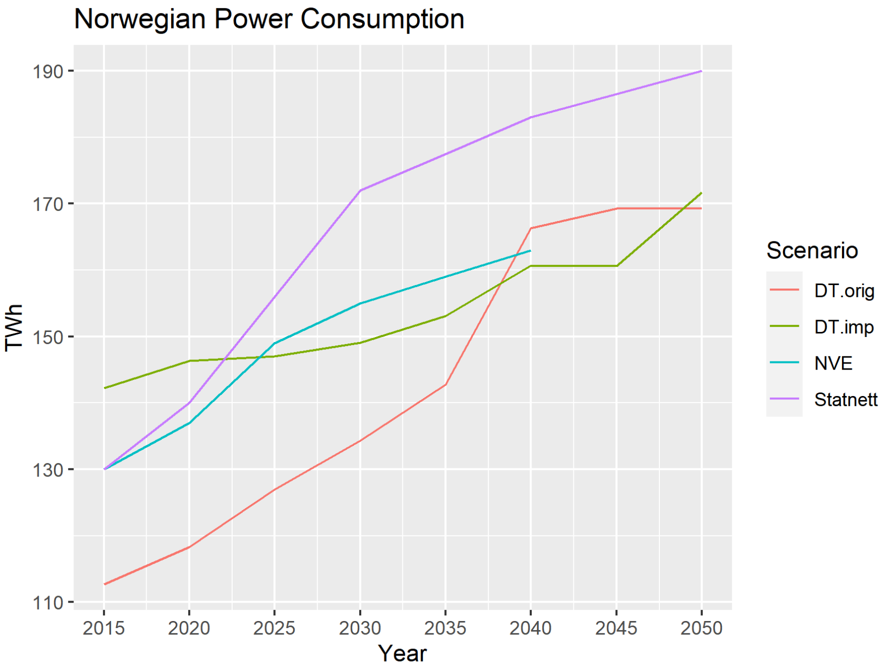

Figure 7.6: Norwegian power consumptions in the original and improved DT scenarios, compared with studies from Statnett and NVE [11, 64]

The base year power consumption in the orig DT results was 17 TWh less than 2015 statistics, while they were 12 TWh higher in the improved version (see Figure 7.6). Therefore, input data related to Norwegian power demand still needs to be updated to describe historical values. Starting in 2025, power consumption in the improved DT scenario is slightly below NVE's projection. In contrast to the openENTRANCE scenarios, Statnett projects a large increase in power demand towards 2050, which is why its results show lower exports than the improved DT scenario despite producing more power (see Table 7.3).

Table 7.3: Comparison of net power exports [TWh]

Scenario	2015	2020	2025	2030	2035	2040	2045	2050
Original DT	-6.8	4.0	9.9	2.5	25	3.8	0.83	0.86
Improved DT	2.4	16	33	30	26	23	21	16
Statnett	15	12	8.5	5.0	8.0	11	14	16
NVE	15	19	18	14	17	19	n/a	n/a

7.4 Results of Disaggregation

7.4.1 Validation and Comparison

Comparison with the Improved Model

Table 7.4 shows the power capacity, production, and consumption results for the improved and disaggregated model versions. The 2015 results, which are the same for each scenario in each model version, show that the Norwegian total installed power capacity and production are higher in the disaggregated results than the improved results. This can be expected due to losses in power trade between regions.

Table 7.4: Comparison between the improved and disaggregated 2015 and 2050 power sector results

Improved	Capacity [GW]	Production [TWh]	Electrolysis [TWh]	Other use [TWh]
Mutual 2015	36	146	0	142
DT 2050	52	189	20	151
TF 2050	54	192	41	127
SC 2050	62	198	22	144
GD 2050	58	196	29	148
Disaggregated				
Mutual 2015	39	151	0	142
DT 2050	54	192	10	151
TF 2050	51	187	22	127
SC 2050	61	197	12	147
GD 2050	61	205	23	149

The 2050 total power consumption is lower in all scenarios in the disaggregated compared to the improved results. Table 7.4 shows that this is due to larger amounts of power consumed for electrolysis in the improved results. Hydrogen is costly to trade, so it is expensive to produce hydrogen in one Norwegian region that is consumed in another. The regions in the disaggregated version where there is a large electrolysis potential, are not necessarily the same regions that require large amounts of hydrogen for decarbonization. Thus, it is less profitable to produce the same amounts of hydrogen as in the improved version. In addition, large amounts of the produced hydrogen in the improved results are exported to continental Europe. In the disaggregated version it is less profitable to export large amounts of hydrogen to the continent. This is because the largest potentials for surplus power are in NO4 where the trade distances are larger and consequent costs are higher.

Comparison with NVE's Long-Term Market Analysis

Figure 7.7 shows the 2020 regional power balance in NVE's 2020 long-term market analysis (left) and the disaggregated DT scenario (right). The net trade includes both domestic and international trade for the DT scenario. The regional power consumption allocation is different, and especially for NO1, the disaggregated dataset assumes a higher demand in this region than NVE's model does. Our disaggregation assumptions are based on an NVE report from 2016 [97] which states that the power demand in each bidding zone can be assumed to be proportional to the population. However, the NVE 2020 report is based on TIMES, which has more sophisticated methods for determining factors such as regional power demands. For instance, NVE's model might be assuming that the consumption in densely populated regions such as NO1 is relatively lower due to higher energy efficiencies in denser living situations.

Our results also show higher production values for several regions compared to NVE. A higher modeled consumption in NO1 causes the neighboring regions NO2 and NO5 to produce more power and export to NO1. However, all in all, results show similar trends for regional power production, consumption, and net trade.

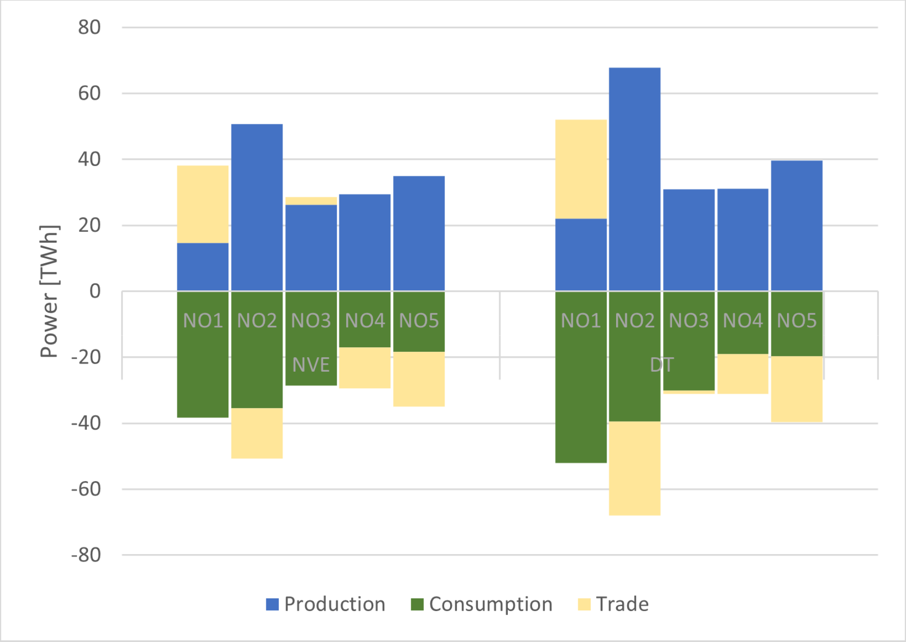

Figure 7.7: Regional 2020 power balance in NVE's analysis and the disaggregated DT scenario

7.4.2 Power Sector

Figure 7.8 shows the regional 2050 power capacities for each scenario. NO1 has the lowest total capacity in each scenario, and NO2 has the highest capacity. This appears to be partly due

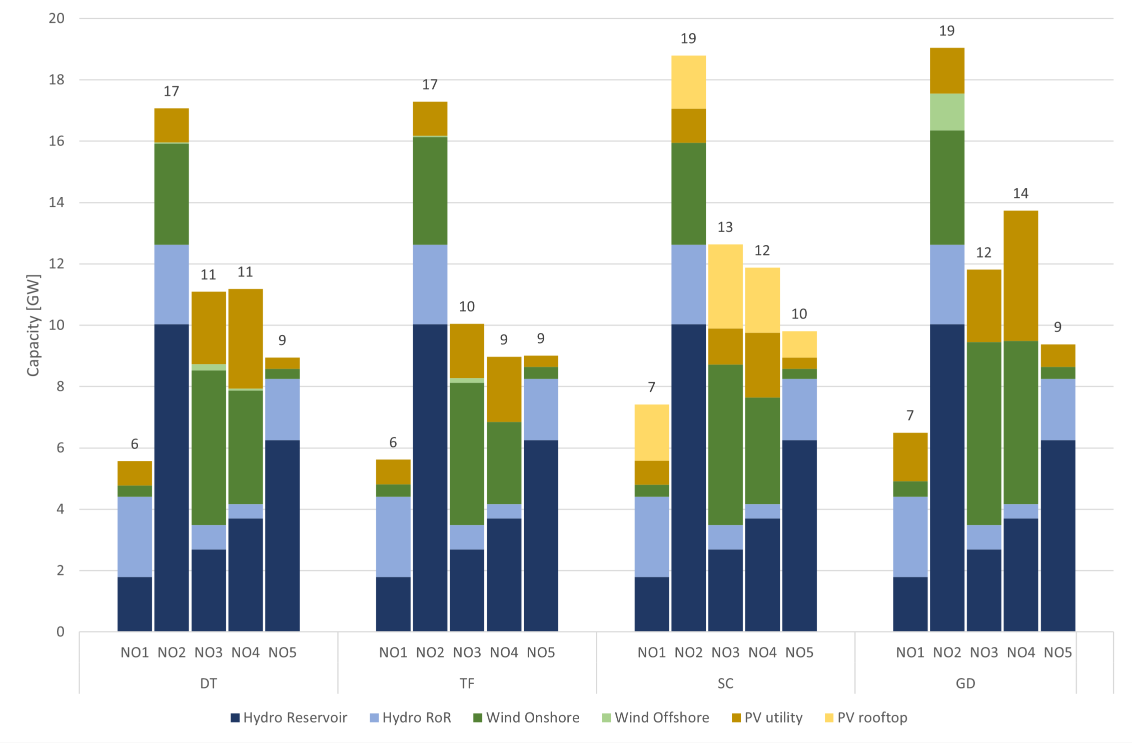

Figure 7.8: Regional 2050 power capacity in the disaggregated scenarios

to the location of hydropower resources, as there are plenty of resources in NO2, and less in NO1. In NO2, NO3, and NO4 there is plenty of onshore wind capacity in all scenarios. These are regions with high availability of land area with good wind conditions. However, these onshore wind results seem high compared to NVE's adjusted prognosis due to the halting of concession processing [52]. The regional onshore wind capacity and production developments between 2015 and 2050 for the DT scenario can be further studied in Figures A.12 and A.11 in the appendix.

In all regions besides NO5, there is a considerable amount of utility PV capacity in all scenarios. This is interesting because currently, there is no utility-scale PV installed in Norway. In general, offshore wind is not an economically viable technology. The only scenario where significant offshore wind capacity is installed is GD, where almost 2 GW is installed in NO2. This appears to be due to the higher 2050 power demand in GD compared with the other scenarios, so this is the only scenario where it is economically viable to deploy offshore wind to cover the load.

Figure 7.9 shows the regional 2050 power production from each technology for each scenario. Most of the power produced is from hydropower, but a large amount is produced from onshore wind as well. The exceptions are NO1, where the wind conditions are poor, and NO5, where the potential for new onshore wind is low according to SINTEF's energy roadmap [98]. The potential in NO5 is low both because the terrain is less suitable for onshore wind installations, and because it is a geographically small region. In NO2 in the GD scenario, a significant amount of the power produced is from offshore wind.

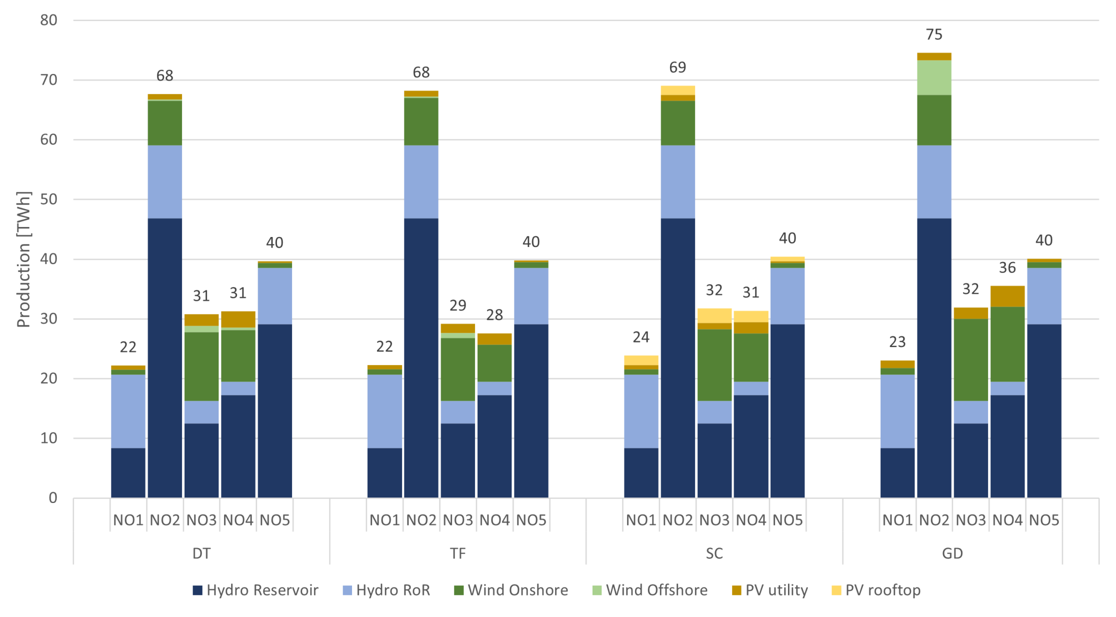

Figure 7.9: Regional 2050 power production in the disaggregated scenarios

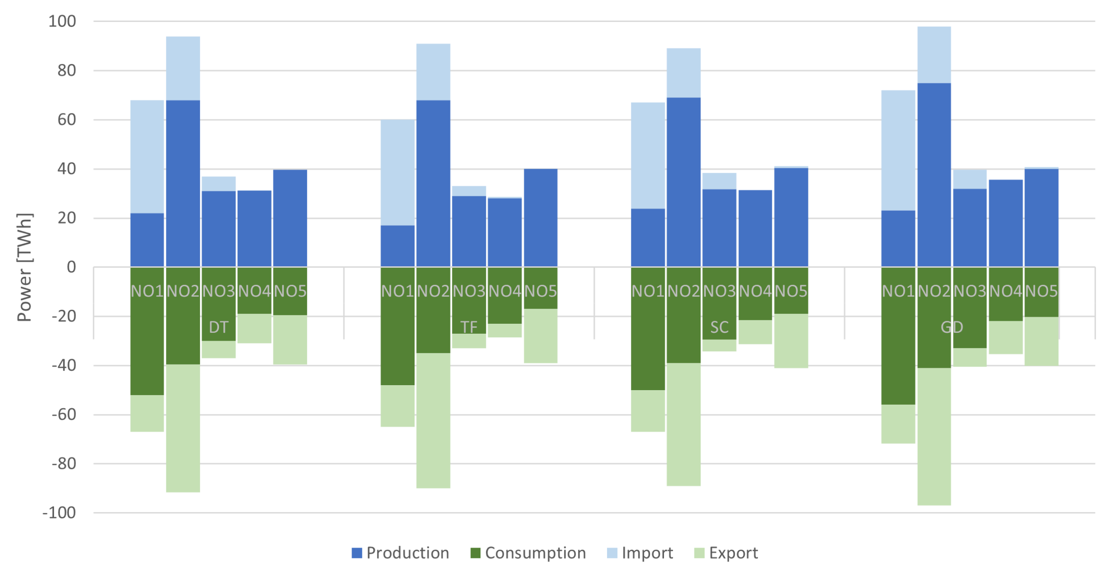

Figure 7.10: Regional 2050 power balance in the disaggregated scenarios

Power Flows Between Regions

In line with the low amounts of power capacity, the production in NO1 is low. However, the consumption is high partly due to the high demand as a result of the population, so NO1 will import power to cover the load (see Figure 7.10). In NO2, the production is high due to the large availability of hydropower. Despite the large share of industries located in NO2, the consumption is relatively low compared to the production, so NO2 will export surplus power. NO4 does not produce very large amounts of power, which is partly because the population and share of industries, and consequent input demand, are low. Even though the potentials for offshore and onshore wind are high in NO4, the grid capacity constrains the possibility to export surplus power to other regions. In NO5, there is plenty of residual hydropower from time periods prior to the modeling period. However, as the region is geographically small, both the population and share of industries are relatively low compared to the other regions. Thus, there is a power surplus which is exported.

The scenarios have similar 2050 results regarding which specific regions power is imported from and exported to. Figure 7.11 shows the cross-regional power trade for 2050 in the DT scenario, where the flow directions represent all scenarios. Despite NO2 having a net power export, the region has a net power import with the UK and Denmark. This is likely due to the high levels of offshore wind deployed in these regions. As illustrated in Figure 7.16, the UK and Denmark together account for almost 30% of the total European offshore wind capacity in 2050. Thus, NO2 likely imports cheap power from the UK and DK when there is a surplus in wind power production, and exports power to other countries when the prices are high. It could also be that NO2 is used as a transition point for power export from the UK to other countries such as Germany. By use of a power market model with a high temporal resolution, this should be studied further.

Figure 7.11: Norwegian 2050 total power trade [TWh] in the disaggregated DT scenario

For further inspection of the disaggregated power capacity and production results, interactive maps can be found in the attachments, or at: `https://folk.ntnu.no/akselhso/GeneratedMaps/DisaggregatedResults/`.

7.4.3 Industrial Sector

Figure 7.12 shows the energy consumption in the industrial sector in the DT scenario until 2050. The consumption declines toward 2050, and in 2050 it is almost half that of 2020. This is mostly due to the assumed demand decrease in this sector due to expected higher future energy efficiency in technologies. A considerable amount of fossil fuel is consumed until 2030. However, in 2030, most of this is consumed in technologies with CCS. DT and TF are the only scenarios that enable the use of CCS. It is interesting to see how CCS is used to reduce emissions in fossil fuel-consuming technologies towards 2030, while being entirely replaced with power-consuming technologies by 2050. In all regions except NO1, almost 50% of the 2030 industrial energy consumption is fossil fuels with CCS. As presented in section 2.5.4, political incentives for CCS are likely to be in place soon, so the high CCS development may not be entirely unrealistic.

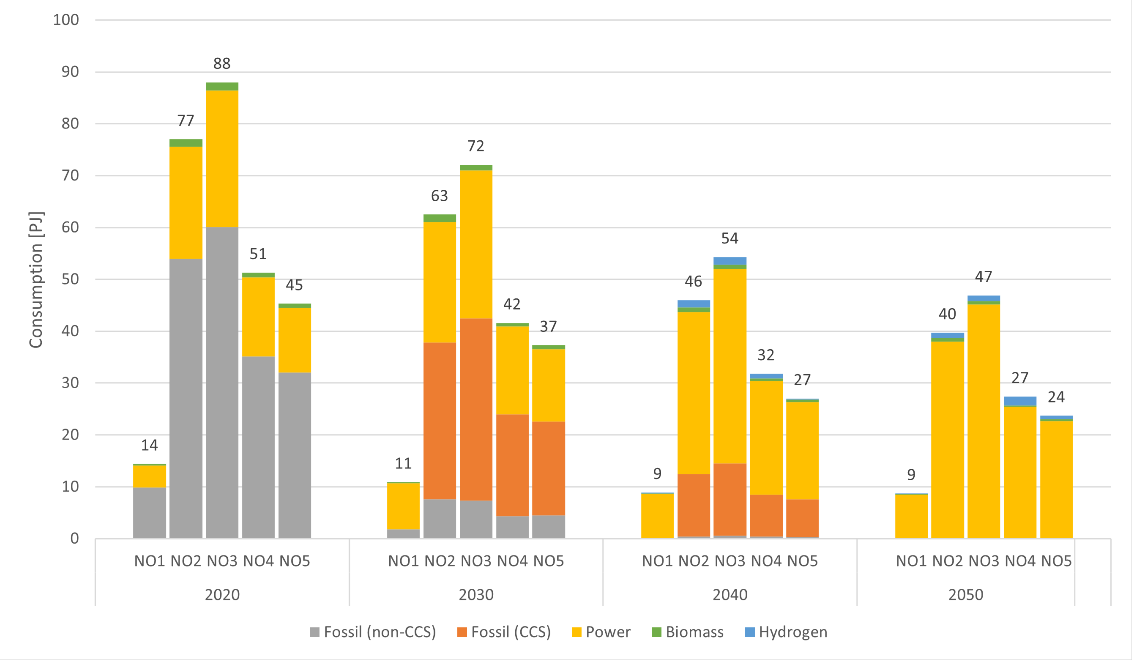

Figure 7.12: Regional industrial energy consumption in the disaggregated DT scenario

7.4.4 Transportation Sector

Figure 7.13 shows the total primary energy consumption for passenger transport towards 2050. Until 2050, the primary energy consumption decreases between 74% and 82% in all scenarios. This is due to assumptions that the transport demand will decrease by between 14% and 32% until 2050, and that technologies will become more energy efficient in the future. In addition, an increase in the use of rail transport rather than road transport contributes to decrease the total energy consumption.

As discussed in section 2.4, TØI's report projects a transport demand increase towards 2050. However, this is based on assumptions that no new incentives will be in place to decrease the demand, and that public travel needs will increase. The openENTRANCE scenarios, on the other hand, assume that the overall mobility demands will decrease. In the DT scenario, this is due to assumptions that policy incentives will be in place to reduce demands. In the SC

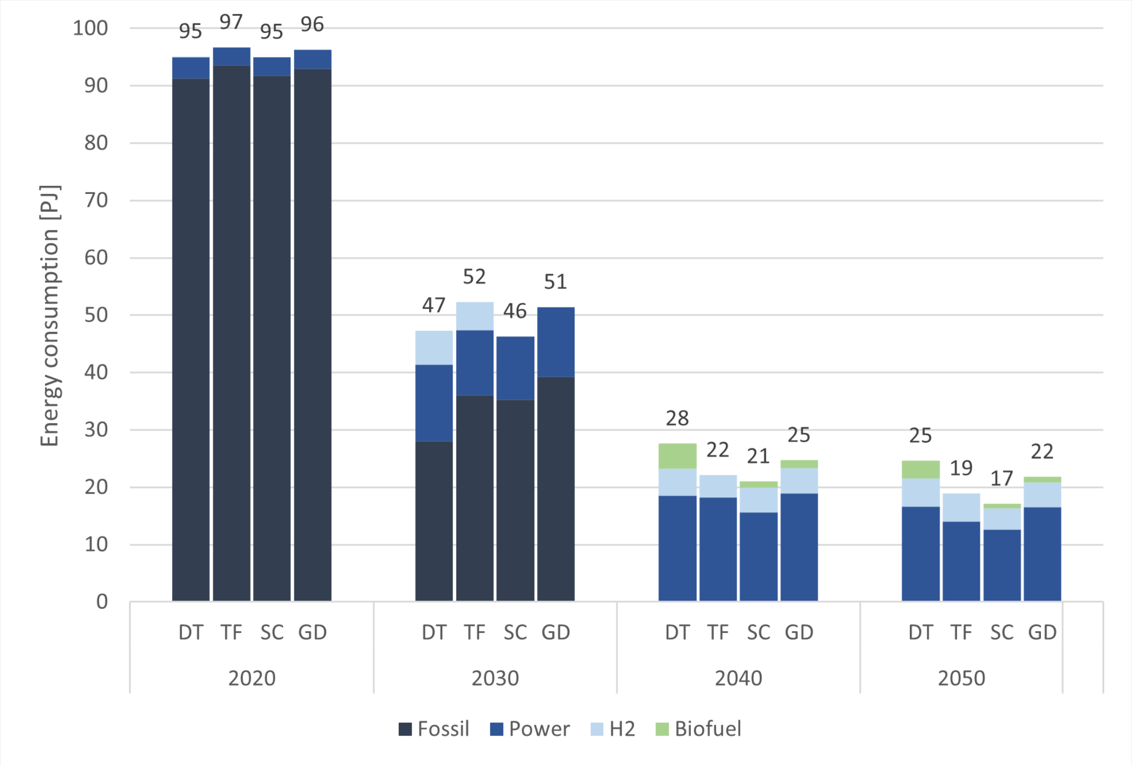

Figure 7.13: Total Norwegian primary energy consumption for passenger transport in the disaggregated scenarios

scenario, this is due to societal willingness to reduce demands due to environmental awareness. However, it is interesting that these assumptions contribute to the results showing such large primary energy consumption reductions in all scenarios.

Figure 7.14 shows the regional energy consumption for passenger transport until 2050. Because of the large population, and consequent high demand for passenger mobility, the highest energy consumption is in NO1. Along the same lines, NO4 has the lowest consumption due to the low population. We see that the decarbonization of the transport sector happens in a similar way in all regions. By 2030, air transport is fueled by hydrogen, rail transport is fully electric, and a large share of road transport is electric. By 2040, the transport sector is completely decarbonized, while the primary energy consumption continues to decrease until 2050.

Decarbonized air transport by 2030 seems overly optimistic. In 2020, Airbus announced that their goal is an airborne zero-emission hydrogen-fueled aircraft by 2035 [100]. Thus, it seems more realistic that air transport may be fully decarbonized closer to 2040. A high share of electric vehicles by 2030 is in line with current policies, as requirements for passenger cars to have zero-emission solutions will be in place within a few years [57]. In actuality, the share of Electric Vehicles (EVs) in Norway will likely be higher than these results indicate. Assuming that passenger road transport in Norway will be decarbonized by 2030, the results indicate that an additional 2.15 megatons CO_2 can be cut. If the air transport demand was supplied by conventional fuels rather than hydrogen until 2040, 0.81 megatons CO_2 would be emitted. Thus, the numbers appear to offset one another. These results are based on the input data assumptions that demands for travel will decrease, but they indicate that the total transport

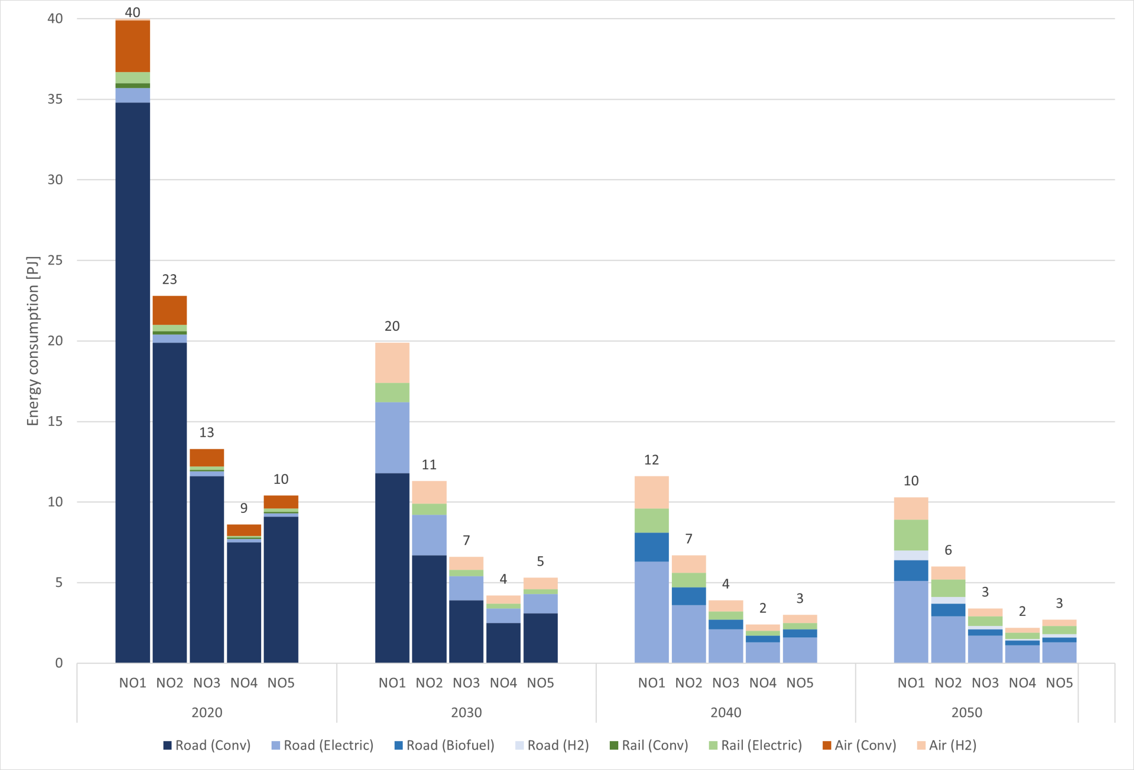

Figure 7.14: Regional primary energy consumption for passenger transport in the disaggregated DT scenario

emission reduction in Norway may be in line with GENeSYS-MOD results if road travel is decarbonized in line with national policies.

7.4.5 Analysis of Disaggregation Results

Oil and Gas Export

Table 7.5: Regional Norwegian oil export in the disaggregated scenarios

	Oil Export [PJ]	
Region	2015	2020-2050
NO1	0	0
NO2	4578	0
NO3	1426	0
NO4	1666	0
NO5	4603	0

In all scenarios, the only year with Norwegian oil export is 2015. Table 7.5 shows the modeling period oil export from each region. NO1 has no petroleum resources, and consequently, no oil export. Looking further at the total European oil trade, no oil is traded after 2015 between any regions. Though not realistic, these results are interesting because they imply that decommissioning oil trade within the near future will be essential in the decarbonization of the European energy system. The natural gas export results (Figure 7.15) show a more gradual decrease than the oil export. However, the quantity of export is halved by 2025, and cut entirely by 2050. These results imply that oil and gas exploration must be halted, in line with findings in the most recent IEA Flagship May 2021 report [101] mentioned in section 2.5.3, to meet the European climate targets. Thus, results indicate that Norway cannot rely on the continuation of value creation from oil and gas export due to a decline in the European market for these resources.

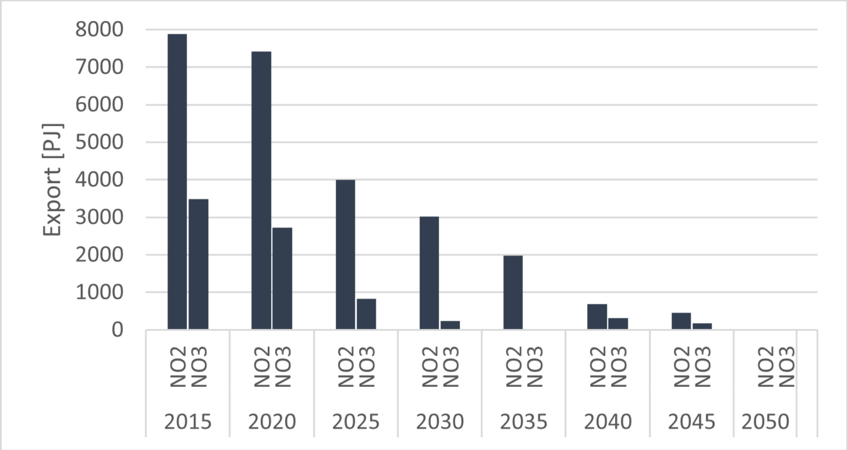

Figure 7.15: Regional natural gas export in the disaggregated DT scenario

Offshore Wind Deployment

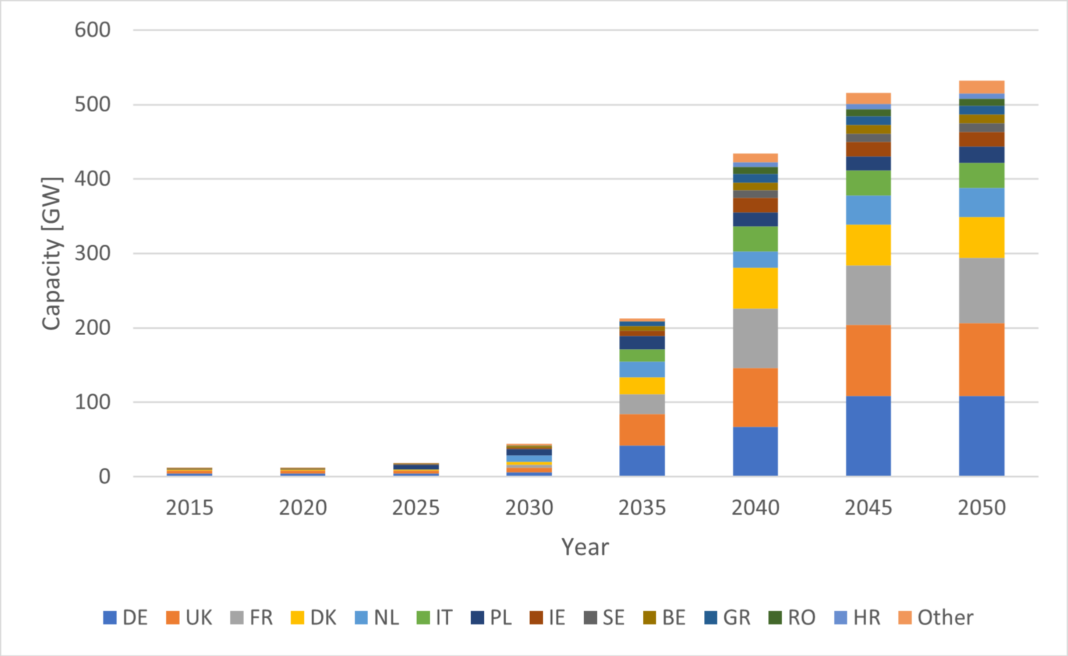

Figure 7.16: European offshore wind capacities in the disaggregated TF scenario

Offshore wind is not prioritized in any of the 1.5 °C scenario results (Figure 7.8). However, results from the TF scenario in Figure 7.16 show a deployment of more than 500 GW offshore wind in Europe by 2050, of which Norway deploys less than 0.1%. As a part of the EU Green Deal, the European Commission presented their Renewable Energy Strategy recently where a target was set for 300 GW offshore wind by 2050 [102]. Our results show much higher values for offshore wind for all scenarios, which may be due to the stricter decarbonization goals in the openENTRANCE scenarios compared to the climate neutrality goal in the EU Green Deal. It is interesting that GENeSYS-MOD sees it as profitable to deploy such large quantities of offshore wind. It can be disputed how realistic this is. Between 2030 and 2035 we see an increase of almost 170 GW, which would require substantial amounts of material resources, new grid transmission infrastructure, and manpower within a short time frame.

Looking at the input data used, Norway shows some of the best wind conditions in Europe. Thus, it appears that offshore wind is not prioritized in Norway because it is not necessary to supply the current power demand, due to the high availability of cheaper hydropower and onshore wind. This implies that there could be substantial amounts of profitable, untapped offshore wind potential in Norway. The GD scenario, which has the highest final power demand, shows significant amounts of offshore wind deployment in NO2 to supply the demand. This suggests that if onshore wind was not an option, or if the power demand was higher in the other regions and scenarios, such as by introducing battery production plants, offshore wind might be suitable to cover the additional load.

Hydrogen Production and Use

Figure 7.17 shows that the highest amount of hydrogen activity is in the TF scenario. This is likely because this scenario assumes great advances in technologies such as electrolysis, resulting in higher efficiencies and lower costs than the other scenarios. NO4 is the largest producer of hydrogen in this scenario, and most of the produced hydrogen is exported to Finland. The other regions produce significant amounts of hydrogen as well, but most of this is consumed locally rather than exported.

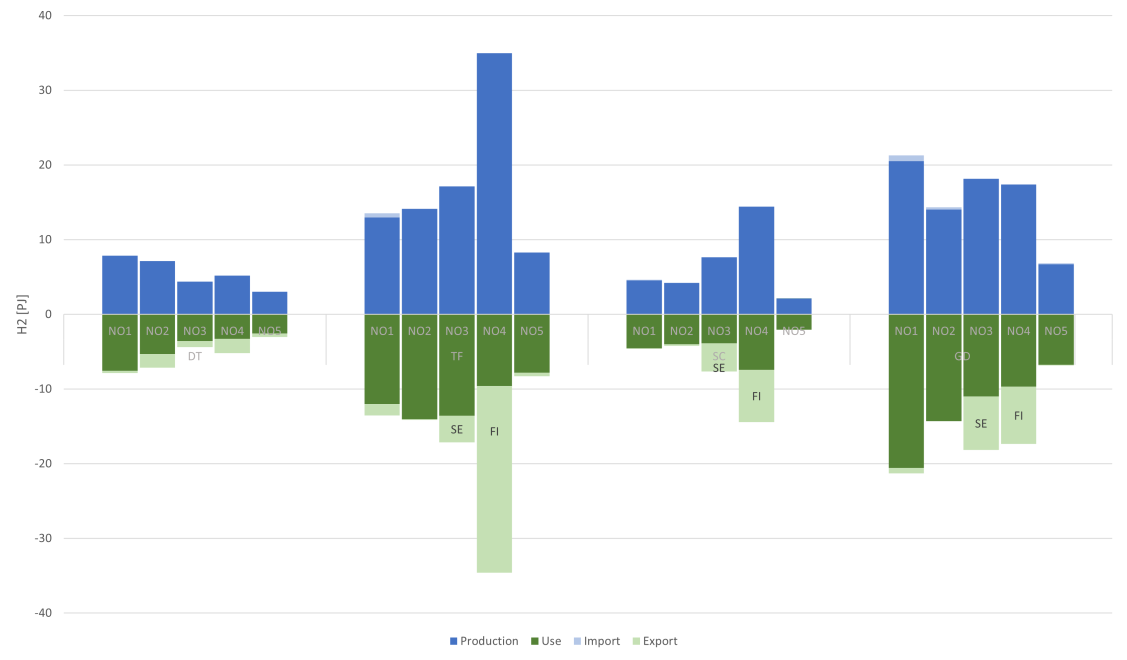

Figure 7.17: Regional 2050 hydrogen production, consumption, import, and export in the disaggregated scenarios

There is a lot of hydrogen production and use in the GD scenario, where NO1 is the largest producer and consumer of hydrogen. NO1 is shown to have a high power demand, but low local power production. Thus, NO1 must import power for local electrolysis to produce hydrogen which is used in freight transportation. None of the regions import significant amounts of hydrogen from other countries. This is in line with Norwegian policies, as it is unlikely that Norway will find it profitable to import hydrogen in the future.

Table A.1 in the appendix shows the main consumers of hydrogen in each scenario. In 2050 in all scenarios, hydrogen is used in freight transportation in NO1 to contribute to decarbonizing the transport sector. In DT and GD, the regions NO2, NO3, and NO5 use hydrogen mainly for freight transport. In TF and SC, these regions consume hydrogen to decarbonize the industrial heating sector. NO4 mainly consumes hydrogen in the industrial heating sector in DT and TF, and produces tradeable syngas in SC and GD.

7.5 Model Performance and Sensitivity

7.5.1 Objectives

Table 7.6: Objective values in each model version

	Version		
Scenario	Original	Improved	Disaggregated
DT	1.342E+07	1.347E+07	1.372E+07
TF	9.457E+06	9.512E+06	9.766E+06
SC	1.118E+07	1.122E+07	1.141E+07
GD	1.136E+07	1.141E+07	1.163E+07

Table 7.6 shows the objective values in each of the dataset versions run for this thesis. The objective values increase with each updated version. This is expected, because "Improved", which includes additional parameter specifications, is more constraining than "Original", and "Disaggregated" includes additional regional parameter specifications and is thus more constraining than "Improved". Running "Disaggregated" greatly increased the model running time and complexity. This is due to five new regions being introduced to the model, each with additional trade possibilities and regional demand specifications. Adding fuel trade costs is another factor that has shown to significantly affect model complexity and running times.

7.5.2 Power Demand Sensitivity

One of the model parameters that has been identified to have the highest level of uncertainty, is the specified annual power demand. This parameter has been defined to have a value of 97 TWh for Norway in 2015. For the TF scenario, the specified power demand decreases to 85 TWh in 2050, and the resulting power production is 187 TWh. This production is low compared to similar studies, mainly due to the assumption of increased energy efficiencies in technologies. However, if we want to model the inclusion of new, power-intensive industries, then the power production results towards 2050 must increase significantly. According to the Prosess21 project, 56 TWh of additional power is needed for Norway to become competitive within battery production, as well as for electrifying the current Norwegian industries [38].

To simulate the effects of a power demand increase in Norway, a sensitivity analysis is performed with the TF scenario in GENeSYS-MOD. Table 7.7 shows the input data for the sensitivity analysis. "Disaggregated" denotes the disaggregated model described in section

Table 7.7: Specified power demand sensitivity input

Demand type	2015	2050
Original	97	85
Constant	97	97
Increasing	97	153

6.2 and analyzed in the previous section of this thesis. "Constant" denotes the power demand version where the total Norwegian power demand is kept constant at 97 TWh per year. "Increasing" denotes the power demand version where the total Norwegian power demand increases by 56 TWh until 2050.

Table 7.8: Objective values and 2050 power variables after altering the power demand

	Specified Power Demand		
	Disaggregated	Constant	Increasing
Objective [M€]	9.766E+06	9.768E+06	9.780E+06
2050 Capacity [GW]	51.0	52.2	55.3
2050 Production [TWh]	187	188	206

Table 7.8 shows the results of this analysis. As expected, the objective value increases when the power demand in the model increases. There is little change in power production between the Constant and Disaggregated versions. As expected, there is a large increase in production in the Increasing version. Figures 7.18 and 7.19 show the 2050 regional power capacities and production for each of these demand types. The difference in power capacity and production between the first two demand types are near non-existent. However, for the Increasing demand type, there are significant differences, and especially for offshore wind. This is in line with the offshore wind discussion in section 7.4.5, where it was assumed that an increase in power demand for Norway would result in offshore wind deployment.

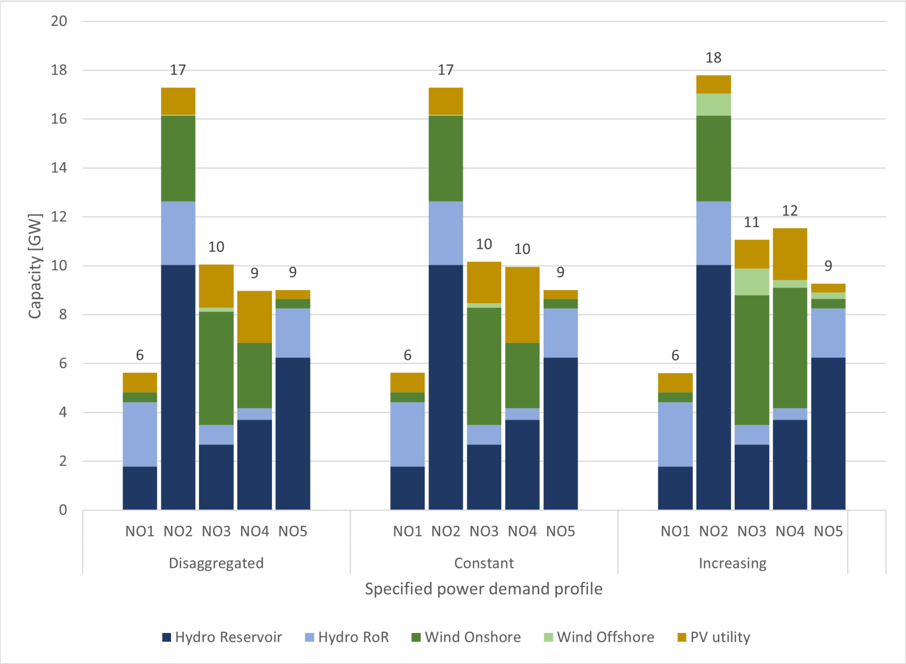

Figure 7.18: Sensitivity power capacity for each type of specified power demand

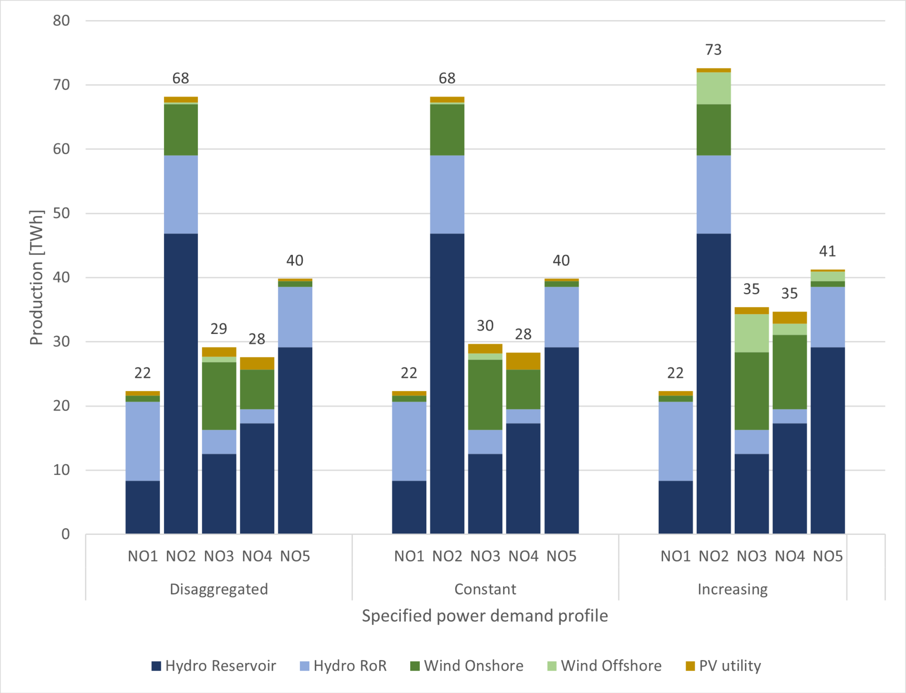

Figure 7.19: Sensitivity power production for each type of specified power demand

Chapter 8

Discussion

8.1 Value Gained by Model Modifications

The openENTRANCE input data for Norway has been significantly improved through the work presented in this thesis. For instance, the original disaggregation of Scandinavia by splitting in three was too simple. Insight and knowledge about Norwegian energy system conditions and policies has streamlined the process of identifying shortcomings in the Norwegian data. Finding data in national studies has significantly impacted the results for Norway. The input data has also been improved in general for all regions by adding trade costs between regions. A study of the impacts of the trade cost modifications at a continental level is not a part of this thesis. Instead, it is a recommendation for improvement for the openENTRANCE project. However, it could be seen from the increased objective values that this impacts the results.

The disaggregated results give indications for how some of the current regional conditions may impact the future energy system. So far, the disaggregation is mainly based on reasonable assumptions rather than regional data. The quality can be further improved beyond this work by access to more regional data. Splitting Norway in the model has paved the way for further work with analyzing the Norwegian energy system at a regional level with GENeSYS-MOD. With more detailed data about factors such as building structure locations and regional transport demand, the work we have done can be used to get insight into the national as well as the specific regions' possibilities and challenges.

The regional disaggregation is useful for common knowledge building and transparent decision-making regarding the energy transition. The openENTRANCE database and the GENeSYS-MOD source code are fully open, making it possible for others to further develop and improve the results. The Norwegian results are developed in a consistent European context, making it possible to understand how Norway may interact with the rest of Europe in the transition. To our knowledge, it is the first time such a model and a dataset is made openly available for Norway. The openENTRANCE results can be used for discussion among policy makers, stakeholders, and the Norwegian society to understand how Norway can do its part of the transition to limit the global temperature increase to 1.5°C.

8.2 Model Limitations

8.2.1 Mathematical Modeling Limitations

As a bottom-up energy system model, GENeSYS-MOD does not account for domestic future economic growth. For Norway, this results in a rapid decommissioning of the oil and gas industry without any suggestions for possible new industries to invest in. Thus, integrating certain macro-economic aspects in GENeSYS-MOD, such as employment and GDP, might result in insights for investment strategies of greater value for decision-makers. One way to address this with the current model, is by increasing the demands for power and heating in the industrial sector in line with the expected population and GDP growth. For Norway, this could simulate the modeling of novel, power-intensive industries such as battery production and data centers.

Extensive energy system optimization models such as GENeSYS-MOD often use a linear approach, as this can decrease the computation complexity significantly compared to non-linear approaches [103]. However, this means that non-linearities must be linearized, which introduces significant simplifications to the model. For example, technology learning curves are given exogenously. However, such curves are dependent of the deployment of the technology calculated by the model. This is therefore not possible to represent in a model like GENeSYS-MOD.

Furthermore, GENeSYS-MOD as a deterministic model with no stochasticity poses additional challenges. Inflows and loads are given as hourly profiles for a single year. However, these factors are heavily dependent on weather conditions each year and cannot be represented accurately with a single profile. In Norway, dry years have a huge impact on the power system, and we may see a net import rather than the usual net export. Particularly cold years cause heating demand increases which puts an additional strain on the power system. Thus, adding stochasticity to some of these factors could increase the validity of the results. However, we have analyzed overall trends toward 2050, rather than looking at specific years and seasons. Thus, this would likely not impact the results presented in this thesis.

8.2.2 Industrial Sector Limitations

GENeSYS-MOD, like many other energy system models, attempts to cover a huge scope. On one hand, this can help give a more holistic view of potential energy system developments and give better indications of investments. On the other hand, this makes it impossible to give a complete, realistic picture of all aspects of each of the modeled sectors and regions. In GENeSYS-MOD, the industry sector is a particular challenge when analyzing regions with industries that differ compared to Germany and central Europe. GENeSYS-MOD models the industry sector based on supplying three temperature ranges of heating demands. For covering the German steel-dominant industry sector, this is sufficient as the main industrial demand is heat. However, there are additional significant demands for power, hydrogen, natural gas, and coal in process industries in the Norwegian industrial sector. Conceptionally, these cannot be replaced by heat. Furthermore, it is very challenging to disaggregate the Norwegian industrial energy demand into the three types of heating demands, as statistics for this are not easily available. Thus, GENeSYS-MOD's current functionalities are currently insufficient for good insights and analysis of the future Norwegian industrial sector.

8.3 Input Data Challenges and Limitations

8.3.1 Working with the Input Data

One considerable challenge of working with GENeSYS-MOD has been to adequately validate and modify its input data. Depending on which scenario is run, the input data files together contain about 74 excel sheets, 38 of which contain regional-specific data for Norway. Furthermore, some of the input parameters are set or overwritten in the GENeSYS-MOD source code, adding to the complexity of the input data. Due to this high complexity, only parameters considered to be highest impacting for our scope have been analyzed. However, this means that there is a lot of data which may impact the results that has been disregarded for this analysis.

8.3.2 General Model Data

Trade costs One significant simplification in the input data is the cost calculation for trading fuels between regions. Originally, there were no trading costs which greatly impacted the results. Despite trade costs being added for the latest model version, they are based on truck transport, which is not representative for gas fuels such as natural gas. The results show that the liquefied form of fuels such as hydrogen and syngas are traded rather than the gaseous form. This could be partly due to the trade cost simplification which might cause the liquefied form of fuels to have a higher trade cost efficiency than the gaseous form. Replacing the current gas fuel trade cost calculations with pipeline trading costs could improve the fuel trade modeling.

Technology efficiencies Looking closer at the input and output activity ratios, certain technology efficiency concerns were raised. There are several instances where technologies with CCS have identical efficiencies to the same technologies without CCS. This is not feasible, as including additional factors to technologies causes the overall efficiency to decrease slightly. Additionally, it was observed that the electrolysis efficiency in the Techno-Friendly scenario is higher than 100% in a few of the later modeling years. It was concluded that it is unlikely that this has a major impact on the results, but it is infeasible, nonetheless.

8.3.3 Norwegian Dataset

During the validation process for the Norwegian data, it was discovered that several of the parameters could not be verified when checked against the sources used by the openENTRANCE project. This was a result of two different challenges. Firstly, Norway is not a part of the EU. This is challenging because several of the sources used in GENeSYS-MOD have analyzed the EU without European non-EU nations such as Norway. Thus, certain Norwegian data in GENeSYS-MOD has been based on data from other Nordic regions. Secondly, version 2.0 of GENeSYS-MOD modeled the aggregated Nordic region of Norway, Sweden, and Finland (named "Scandinavia" in the model). For version 3.0 this region was disaggregated into the individual countries. However, in several instances the disaggregation had not been based on the original sources used. This was particularly noticeable regarding the oil and gas resources. For this reason, it will be necessary to perform a review of the input data. In particular, data for other regions which have been disaggregated for version 3.0 should be inspected.

For this thesis, the Norwegian GENeSYS-MOD data has been updated significantly. However, several parameters have been observed to have unrealistic values and have not been updated for this model version for various reasons. The parameters with the highest level of uncertainty are the industrial heating demands as discussed above. The medium and high heating demands were difficult to validate, and it would benefit the Norwegian results to perform a re-evaluation of these parameters.

Offshore wind potential The offshore wind model capacity potentials are equally high for shallow, transitional, and deep waters. Due to deep waters and steep coasts, Norway has a limited share of available shallow and transitional water depths for offshore wind constructions. However, this did not appear to impact our results which showed exclusively deep offshore wind deployment.

Transportation types The modal split, which defines the base year shares of transportation types such as road, rail, and air, has not been validated, and appears to differ from TØI's transport report. The modal split can also be updated to represent a higher share of EVs in Norway until 2030, which will impact the modeled transport sector decarbonization.

Run-of-river The run-of-river profile for Norway appears to be invalid, for example it does not depict the spring flood. This may have an impact when analyzing the results using a high time resolution. However, our results have been analyzed with a yearly resolution, so it is not likely that this significantly impacts our results.

Onshore wind Our results indicate that high amounts of Norwegian onshore wind can be deployed in all scenarios and bidding zones. However, no new onshore wind power concessions will be given in the next 6 or 7 years. Thus, after 2021, no new onshore wind may be deployed until 2030. This can be implemented in GENeSYS-MOD with region-specific constraints for Norway, but it is difficult to predict whether this would result in model infeasibilities. Thus, it would be interesting to model this scenario and evaluate whether GENeSYS-MOD sees it as essential for decarbonization that onshore wind is deployed in Norway within the next 5-10 years.

8.3.4 Disaggregated Dataset

For the disaggregated Norwegian data, many assumptions had to be made that impact the results. Firstly, all mobility and power demands have been disaggregated based on population. This is a good assumption for the analyses in this thesis, but does not give an accurate representation, as seen when comparing with NVE's analysis. The sets of parameters that were particularly challenging to redefine based on the five new regions were the hourly data profiles. The new data from renewable.ninja for offshore wind showed hourly profiles that were on average 50% better than for any other European region. This resulted in unrealistically high offshore wind results. The new PV and onshore wind profiles also showed inconsistencies. Consequentially, these inputs had to be discarded and the original hourly profiles had to be used for the new regions.

Gas trade assumptions can also be improved. Despite NO4 and NO5 having allocated natural gas resources based on NPD sources, they do not have the possibility to trade these resources. This is due to the gas trade infrastructure assumptions for Norway being based on data from Gassco, which does not show pipeline trade from these two regions. This can be improved by either allowing gas trade between the Norwegian regions, or by allocating the gas resources in

NO4 and NO5 to the neighboring regions NO3 and NO2, respectively, instead. Adjusting the gas trade would likely not change the rapid export decrease trend, but it might increase the level of export in the early modeling years.

8.4 Increased Granularity Implications

Modeling one geographical area with a higher spatial resolution than the remaining regions may have implications on the results of neighboring regions. Increased granularity produces overall better results for insight into the future Norwegian energy system, but neighboring regions must also be analyzed at a similar granularity to ensure that the results are feasible. In particular, the neighboring regions of Sweden and Denmark are not disaggregated in our model, but these countries also have domestic bidding zones. This means that the trade with these regions might be overestimated due to bottlenecks in the domestic Swedish or Danish grid.

8.5 Future Norwegian Bidding Zone Developments

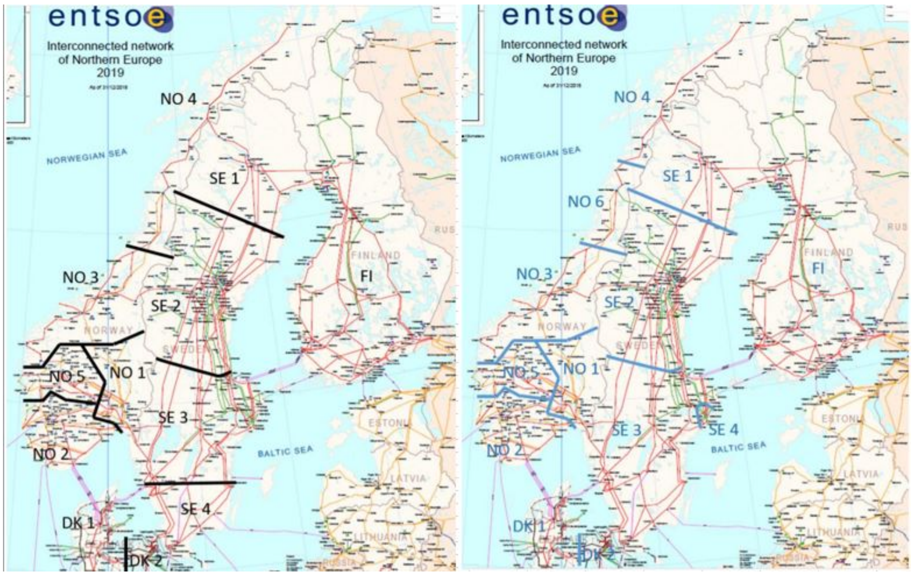

Figure 8.1: Scandinavian current and suggested future bidding zones. Source: Statnett [104]

As seen in our results, there is a lot of new capacity modeled in NO4, but little new industry, which causes a high increase in the NO4 power export. This is in line with Statnett analyses, which indicate that congestions out of NO4 will increase in the future [104]. To manage bottlenecks more efficiently, they propose to divide NO4 into two regions. Figure 8.1 shows the current bidding zones (left) and the suggested future bidding zones (right). Dividing NO4 into two zones will enable better regional detail and facilitate making recommendations about where in Northern Norway new power-intensive industries should be located, and where new power capacities should be deployed. For energy system modeling in GENeSYS-MOD, this could give a better picture of the available resources versus demands in the northernmost region and contribute to results of higher value. Furthermore, it is possible that in the future, the Norwegian bidding zones will be disaggregated even further, potentially resulting in a nodal power market rather than the current zonal market.

Chapter 9

Conclusion

In this thesis, the GENESYS-MOD and openENTRANCE decarbonization scenarios for how the Norwegian energy system should develop to reach the 1.5°C target in a European context are verified and validated. This work has improved the input dataset for Norway and has also identified modeling weaknesses. Since GENeSYS-MOD and the scenarios are fully open, this work can be brought further by others.

The results of this thesis indicate that if Norway aims to reach the 1.5 °C target, measures must be taken immediately. With an assumption that no new industries will be commissioned, the power production increases by between 36 and 46 TWh, due to decarbonization through electrification and hydrogen use. This additional power is primarily supplied by onshore wind and PV deployment.

The oil and gas industry is expected to decline rapidly as a result of decreasing European demands due to decarbonization across the continent. Even though electrification of this sector is necessary for Norwegian emission reduction, it is even more critical to find alternative industries to replace this sector in terms of value creation and employment. The results presented in this thesis suggest that Norway has the potential to commission power-intensive industries in NO2, NO3, and NO4, supplied by offshore wind power.

To answer the first research question, the openENTRANCE implementation of GENeSYS-MOD can be used to get useful insights about the future Norwegian energy system. By improving the input dataset, modeled power productions and consumptions are now in line with statistical data for the base year. Also, the scenario results show trends that are more similar to trends in published Norwegian power market analyses. Insights include that it may be possible to supply the future power demand increase with onshore wind and PV, given that restrictions for onshore wind will cease and that new, power-intensive industries will not be commissioned.

To answer the second research question, the insights for the Norwegian energy system were improved by disaggregating Norway into the five bidding zones. Hydrogen showed to be an important energy carrier to decarbonize passenger air travel, freight transportation, and the industry sector in all regions. In regions with low power production potential, such as NO1, it can be more profitable to import power for electrolysis than it is to import hydrogen produced in a different region. With a 2050 hydrogen surplus of 28 PJ in the Techno-Friendly scenario, NO3 and NO4 show the potential to become important exporters of hydrogen to the Finnish and Swedish markets.

Chapter 10

Recommendations for Further Work

If the GENeSYS-MOD input data modifications suggested in this thesis are used for future openENTRANCE scenario modeling, enabling Norwegian onshore wind political constraints may be necessary. These can be added directly in the GAMS code to limit the deployment of new onshore wind between 2020 and 2030. If this is the case, then the residual capacity for onshore wind in Norway should also be updated with 2021 capacities. If these onshore wind constraints are added, it will be interesting to see if GENeSYS-MOD is still able to find a feasible solution for decarbonizing the Norwegian energy system. If no feasible solution can be found, it may imply that the current Norwegian onshore wind policies are not sustainable.

A more suitable modeling of the Norwegian industrial sector that can provide better insights is necessary. The industrial sector can be improved by adding industrial-specific power and resource demands, as well as energy demands for offshore platforms. If statistics for medium and high temperature industrial heat consumption are found, then the demands for these parameters can be improved. In addition, enabling new power-intensive industries such as battery production and data centers can provide insight into how the energy demand from new industries will impact the development of the energy system.

Several model parameters can both be validated and improved in further work. GENeSYS-MOD requires a huge amount of input data, and it has not been possible to validate the entire dataset for this thesis. Parameters that should be validated for the general model include the technology efficiencies and trade costs. Parameters that should be validated for Norway include the hourly profile for run-of-river, the modal splits, and industrial heating demands. For the disaggregated dataset, the hourly profiles for solar irradiance and wind should be validated. Norwegian gas trade modeling can be further improved. Regional power consumption statistics could be used to further improve the disaggregated power demands.

Coupling GENeSYS-MOD with a sectoral model, such as a power market model with higher temporal resolution, could be an interesting continuation of the work presented in this thesis. An iteration of analyses between GENeSYS-MOD and a power market model will improve the feasibility insight of the GENeSYS-MOD results. It would be particularly useful to investigate factors that vary depending on market situations, such as power trade and energy storage.

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Appendix A

Additional Material

A.1 Plots Related to Verification

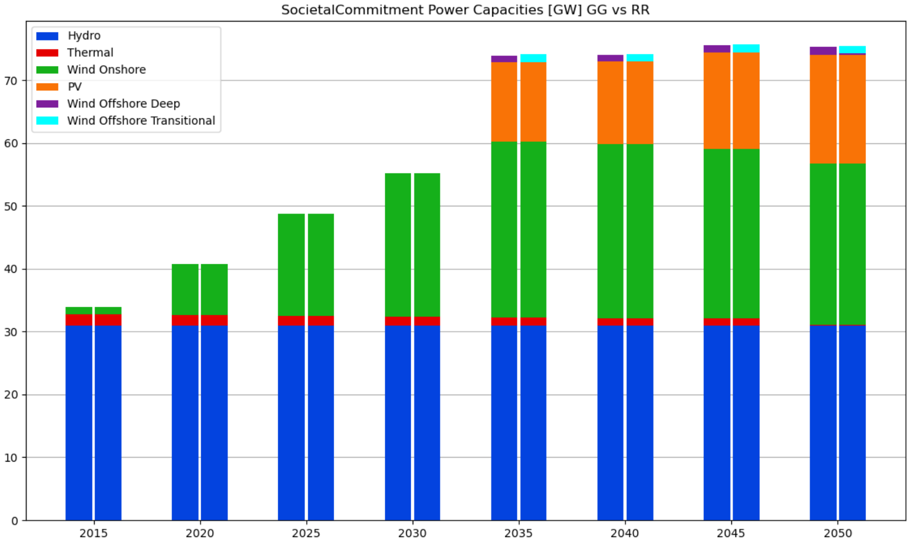

Figure A.1: Comparison of generated and received power capacity results for aggregated technologies in Norway

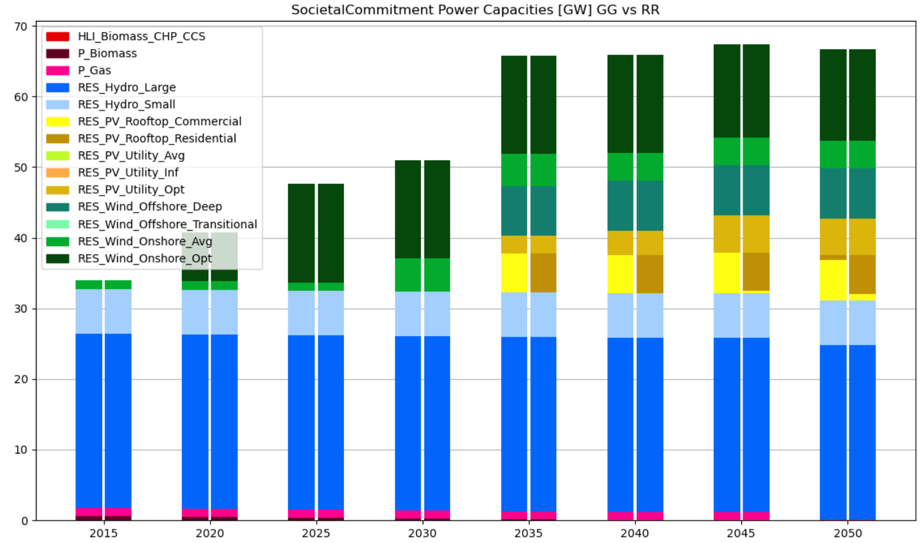

Figure A.2: Comparison of generated and received power capacity results for all technologies in Norway

A.2 Plots of Original Results

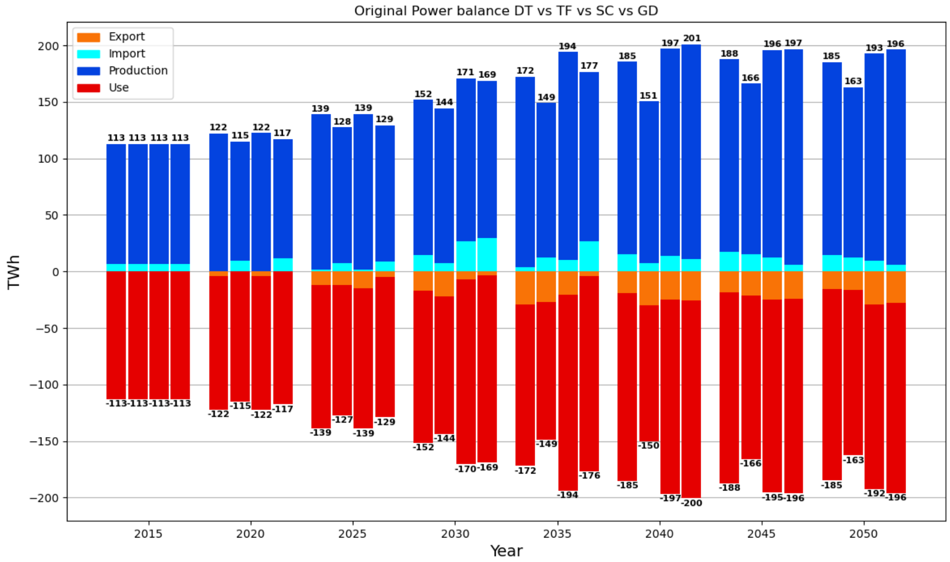

Figure A.3: Norwegian power balance in the original scenarios

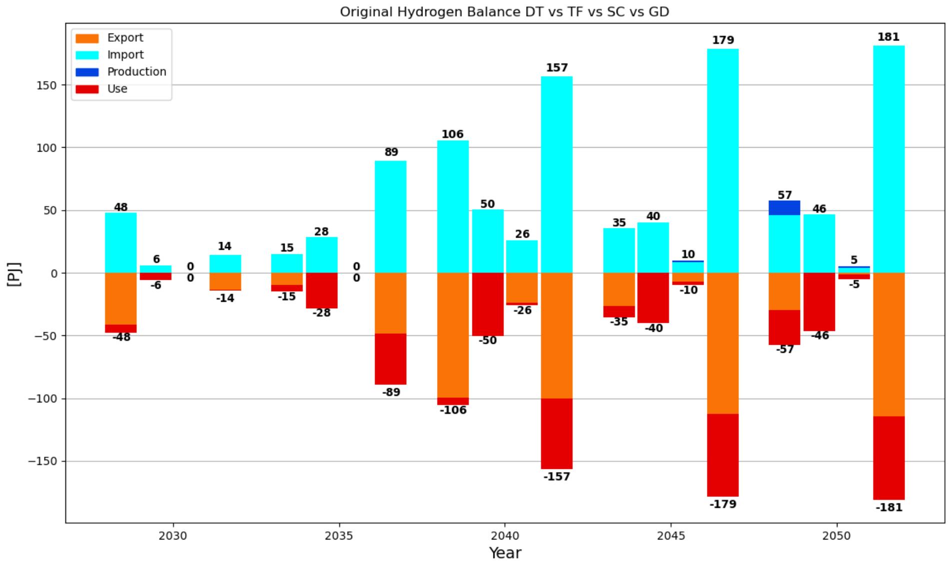

Figure A.4: Norwegian hydrogen balance in the original scenarios

A.3 Plots of Improved Results

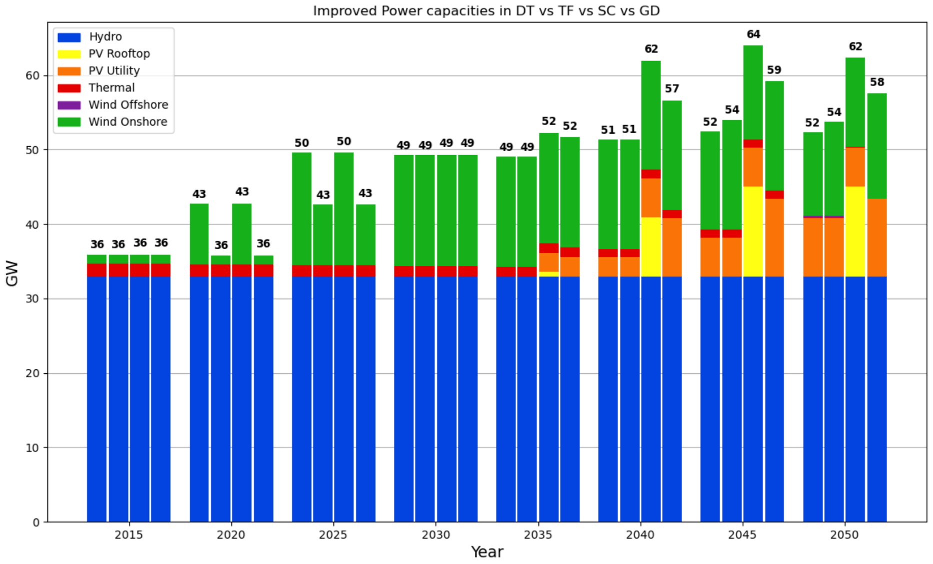

Figure A.5: Norwegian power capacities in the improved scenarios

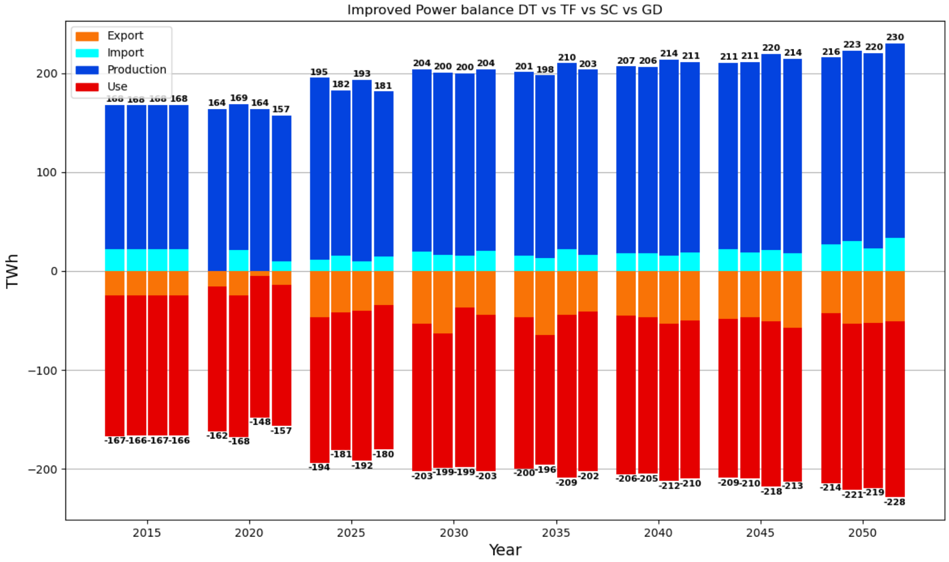

Figure A.6: Norwegian power balance in the improved scenarios

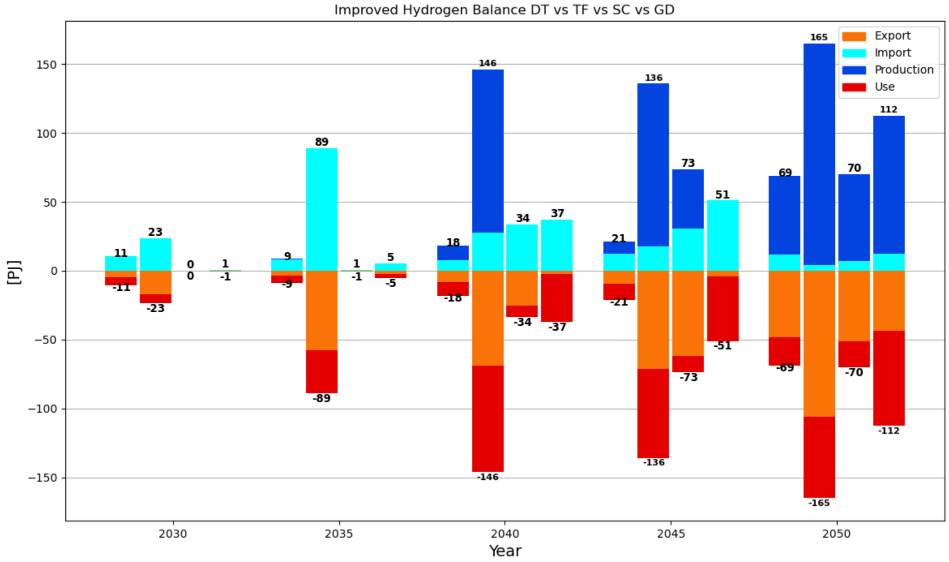

Figure A.7: Norwegian hydrogen balance in the improved scenarios

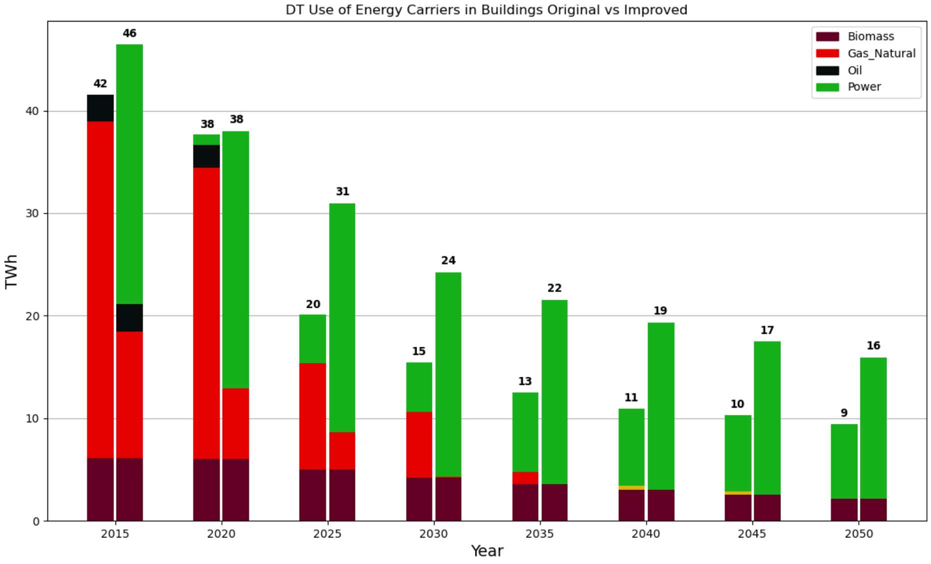

Figure A.8: Norwegian use of energy carriers in buildings in the original and improved DT scenarios

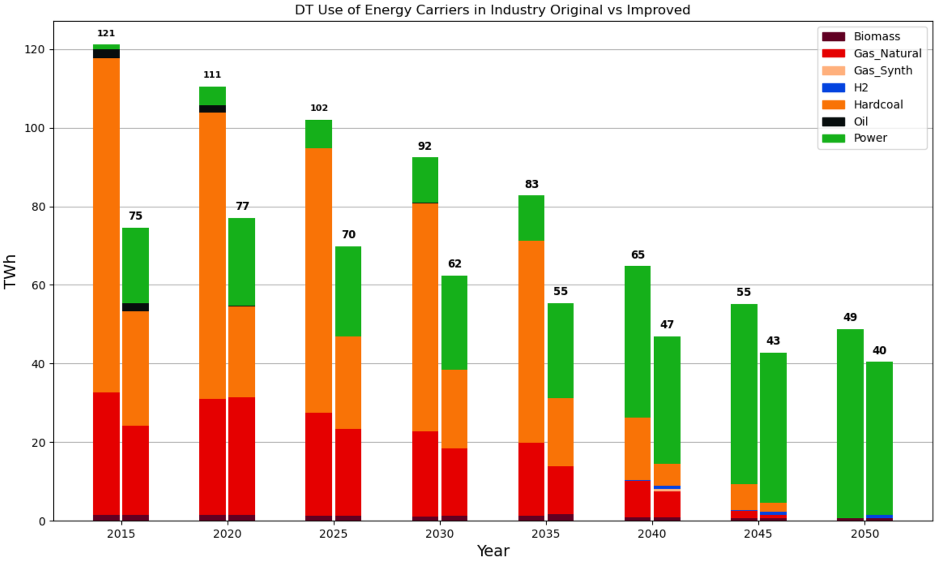

Figure A.9: Norwegian use of energy carriers in industry in the original and improved DT scenarios

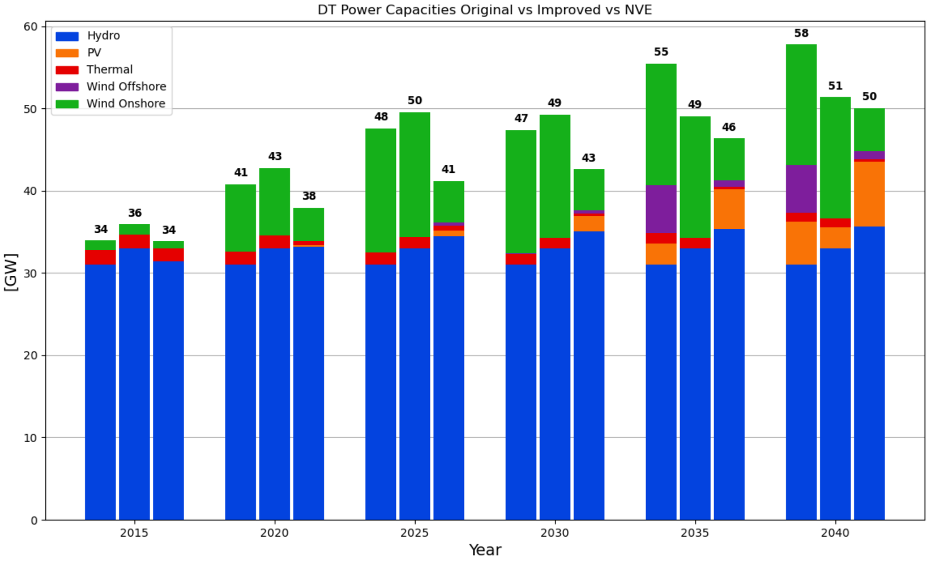

Figure A.10: Power capacities in the original and improved DT scenarios compared with NVE's projections [11]

A.4 Disaggregation Results

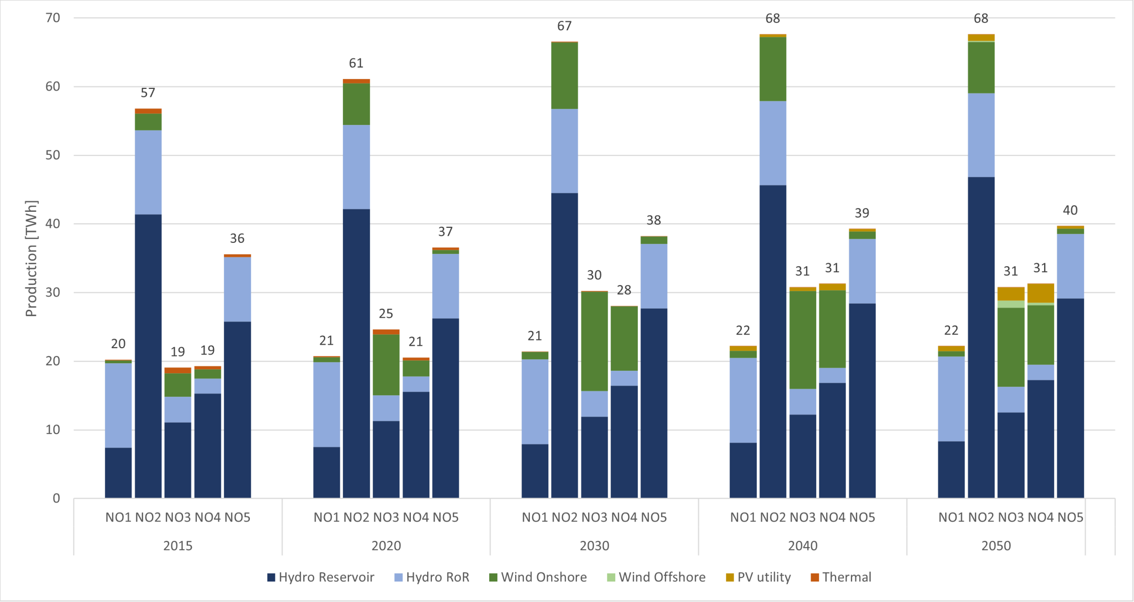

Figure A.11: Regional power capacities in the disaggregated DT scenario

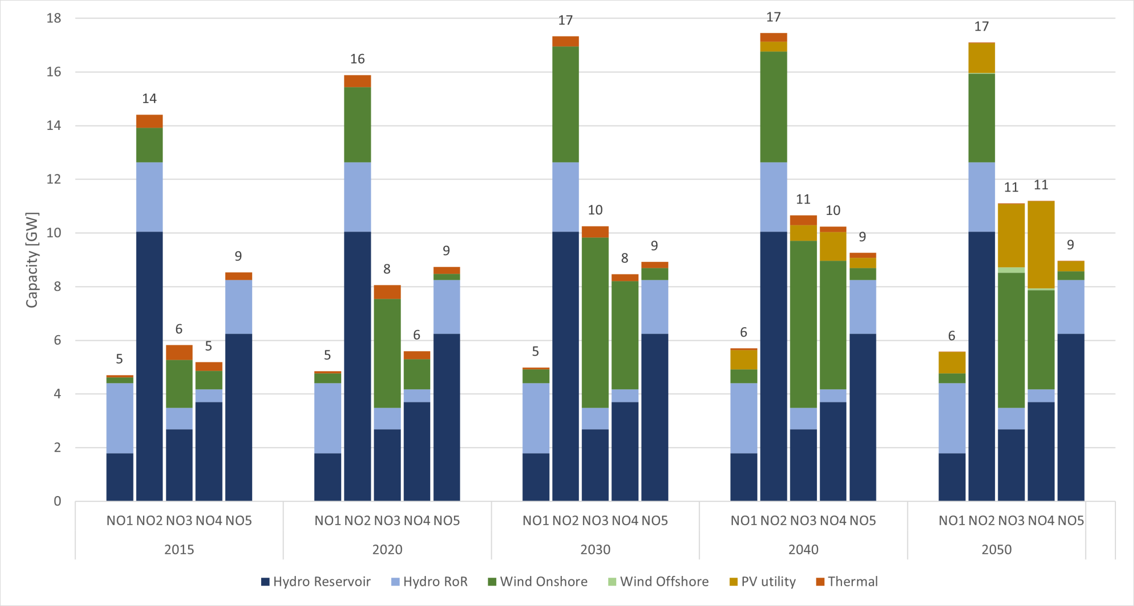

Figure A.12: Regional power production in the disaggregated DT scenario

Table A.1: Regional 2050 hydrogen production, consumption, and trade [PJ] in the disaggregated scenarios

Scenario	Region	Prod.	Use	Import	Export	Main consumer
GD	NO1	20.0	20.1	0.8 (DK)	0.7 (FI)	Road freight
	NO2	13.6	13.9	0.3 (DK)		Road freight
	NO3	17.8	10.4		7.4 (SE)	Road freight
	NO4	17.7	10.1		9.3 (FI, SE)	Methanation
	NO5	6.3	6.4	0.1 (DK)		Road freight
SC	NO1	4.7	4.5			Road freight
	NO2	4.1	3.7		0.3 (CZ)	Road freight
	NO3	10.6	4.2		6.4 (SE, DE)	Industrial heating
	NO4	12.3	6.1		6.2 (FI, SE)	Methanation
	NO5	2.1	2.0		0.1 (NO1, CZ)	Industrial heating
DT	NO1	7.8	7.6		0.2 (DE, PL)	Road freight
	NO2	7.8	5.3		2.5 (DE, PL)	Road freight
	NO3	4.5	3.6		0.9 (DE, PL)	Road freight
	NO4	5.1	3.3		1.8 (DE, PL, SE)	Industrial heating
	NO5	3.0	2.6		0.5 (DE, PL)	Road freight
TF	NO1	13.6	12.6	0.5 (NO2, NO5)	1.5 (SE, FI)	Road freight
	NO2	18.7	18.5		0.2 (NO1)	Industrial heating
	NO3	22.0	18.4		3.6 (SE, FI)	Industrial heating
	NO4	37.6	11.9		25.7 (FI, SE)	Industrial heating
	NO5	10.9	10.3		0.6 (NO1, SE)	Industrial heating

A.5 Other Tables

Table A.2: Power production [TWh] according to NVE's model

Energy Source	**2015**	**2020**	**2022**	**2025**	**2030**	**2040**
Hydro	138	140	142	145	146	149
Wind	3	14	18	20	20	24
PV	0	0	0	1	2	7
Thermal	4	2	2	2	1	1
Sum	**145**	**156**	**162**	**167**	**169**	**182**

Appendix B

GENeSYS-MOD Modifications

Trade Capacity Defines the capacities for trade between two regions in a specific year and for a specific fuel. See Figure B.1 for improved power trade capacities between Norwegian bidding zones domestically and internationally. See Table B.1 for the improved and disaggregated gas export (pipeline) capacities.

Table B.1: Improved gas trade capacity [PJ] from Norway to other regions. Data source: Gassco [94]

Region	BE	DE	FR	UK
NO	616	2355	800	2577
NO2	616	2355	800	
NO3				2577

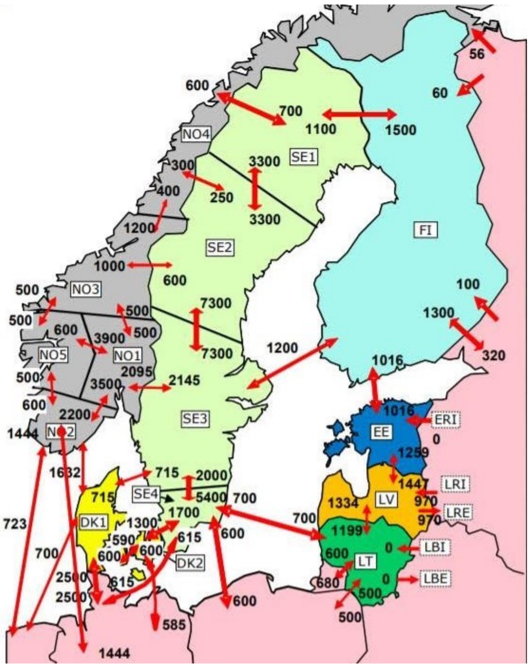

Figure B.1: Power trade capacities between the Norwegian bidding zones [MW]

Regional Base Year Production Describes how much of a fuel must be produced by specific technologies in the base year per region. See Table B.2 for improved base year low temperature residential and industrial heating sources.

Table B.2: Improved Norwegian base year heating production

Technology	Fuel	Value [PJ]	Source
HLR Oil Boiler	Heat Low Residential	0	Policy [56]
HLI Direct Electric	Heat Low Industrial	64.8	NVE [28]
HLR Direct Electric	Heat Low Residential	109.4	NVE [28]

Residual Capacity The capacity left over from periods prior to the modeling period. See Table B.3 for improved and disaggregated base year capacities and future residual capacities based on current capacities of reservoir hydro, run-of-river hydro, onshore wind, and Pumped Hydro Storage (PHS). Capacities for direct electric heating technologies are calculated based on the necessary base year production in Table B.2.

Table B.3: Improved residual capacities [GW]

Technology	Region	2015	2020	2025	2030	2035	2040	2045	2050	Source
HLI Dir. El.	NO	2.1	1.9	1.5	0.9	0.4	0.2	0.0	0.0	Table B.2
HLR Dir. El.	NO	3.5	3.2	2.5	1.5	0.7	0.3	0.1	0.0	Table B.2
PHS	NO	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	NVE [87]
	NO1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	NO2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
	NO3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
	NO4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	NO5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
Hydro Large	NO	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	TIMES
	NO1	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	
	NO2	10	10	10	10	10	10	10	10	
	NO3	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	
	NO4	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	
	NO5	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	
Hydro Small	NO	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	TIMES
	NO1	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	
	NO2	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	
	NO3	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
	NO4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
	NO5	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	
Wind Onshore	NO	4.0	4.0	3.9	3.6	3.5	3.1	0.0	0.0	NVE [105]
	NO1	0.2	0.2	0.2	0.2	0.2	0.2	0.0	0.0	
	NO2	1.3	1.3	1.3	1.3	1.3	1.0	0.0	0.0	
	NO3	1.8	1.8	1.7	1.5	1.4	1.4	0.0	0.0	
	NO4	0.7	0.7	0.7	0.6	0.6	0.5	0.0	0.0	
	NO5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Model Period Activity Max Limit Maximum total activity for the complete model period per region. Table B.4 shows the improved and disaggregated oil and gas resources.

Table B.4: Improved resource activity limits for oil and natural gas. Data source: NPD [95]

Resource	Region	Value [PJ]
Oil	NO	61924
	NO1	0
	NO2	23119
	NO3	7268
	NO4	8417
	NO5	23119
Natural Gas	NO	79199
	NO1	0
	NO2	25660
	NO3	19640
	NO4	8240
	NO5	25660

Regional CCS Limit Describes how much carbon can be stored per region. Table B.5 shows the improved and disaggregated CCS potential.

Table B.5: Improved CCS limits. Data source: NPD [96]

Region	Value [megatons]
NO	56800
NO1	0
NO2	23400
NO3	4400
NO4	7300
NO5	21700

Specified Annual Demand The annual demand for each output fuel. Hourly Data parameters distribute this demand over the timesteps. Table B.6 shows the improved base year demands for power, Heat Low Industrial (HLI), and Heat High Industrial (HHI) as calculated in section 5.3.3. The development profiles toward 2050 use the same factors as the original specified annual demands for these fuels.

Availability Factor Maximum time a technology may run for the whole year. Often used to simulate planned outages. GENeSYS-MOD will choose when to run or not run. Table B.7 shows the availability factors for large hydro calculated using formula 5.1 in section 5.3.1.

Table B.6: Calculated NO specified annual demand for power, HLI, and HHI

Scenario	Fuel	2015	2020	2025	2030	2035	2040	2045	2050
DT	Power	349	346	335	325	315	306	296	286
	HLI	126	123	113	99	87	76	67	60
	HHI	64	59	56	52	47	43	39	37
TF	Power	349	346	339	332	325	319	312	306
	HLI	126	123	115	103	92	83	75	68
	HHI	64	59	57	54	50	47	43	42
SC	Power	349	346	334	322	310	299	288	277
	HLI	126	123	111	97	84	73	63	56
	HHI	64	59	55	51	46	41	37	34
GD	Power	349	346	342	339	335	332	329	325
	HLI	126	123	115	103	92	83	75	68
	HHI	64	59	57	54	50	47	43	42

Table B.7: Calculated availability factors for NO Hydro Large

	2015	2020	2025	2030	2035	2040	2045	2050
Availability Factor	0.47	0.48	0.50	0.51	0.51	0.52	0.53	0.53