NTNU – Trondheim
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Power System Impacts of variable renewable Energy Sources towards 2050

With special emphasis on wind and solar utilisation and grid costs

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Master of Energy and Environmental Engineering
Submission date: Januar 2014
Supervisor: Gerard Doorman, ELKRAFT
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Abstract

The European Union(EU) has set an ambitious goal of reducing the Green House Gas(GHG) emissions with at least 80-95% in 2050 compared to 1990 levels. Due to the difficulties of avoiding all emissions in other sectors such as transport and agriculture the power sector should be close to 100% renewable. For the European energy system this means that the fossil fuel power has to be strongly reduced and that a vast amount of wind and solar power would have to be installed towards 2050. Due to the long life times of fossil fuel powered plants, 2050 is only one investment cycle away. It is therefore important that the possibilities and challenges of the 2050 energy system are investigated today.

A scenario giving the installed capacities in each country for the energy system in 2030 is given in the Scenario Outlook and adequacy forecast(SO&AF) published by the European Network of Transmission System Operators for Electricity(ENTSO-E). The energy system in 2030 is also analysed in the Twenties project by SINTEF Energy Research. In the “Energy Roadmap 2050” produced by the European Commission(EC) a scenario with a high share of renewable energy towards 2050 is presented. The main aim of this thesis is to analyse how the further development of wind and solar power after 2030 will influence some key parameters in the power system. One of the focus areas is on how the utilisation of wind and solar power will change when increasing the capacities. Another important issue is how the increased amount of wind and solar influence the thermal production, and how the production mix might change from 2030 to 2050. The flow in High Voltage Direct Current(HVDC) corridors and how the increased amounts of wind and solar towards 2050 influence this flow is another important topic. The last issue that is treated in this thesis is how the costs and bottleneck costs changes as the production mix is changed from 2030 to 2050 levels, especially how the wind and solar influence the congestion costs separately or combined.

This study were performed by doing simulations with the Power System Simulation Tool(PSST) model. First a base scenario was simulated, using 2030 data from the SO&AF. Then simulations were done with wind and solar capacities set to 2050 level, separately and combined. This was to reveal the effect the wind and solar power has on the parameters in the power system. In the last scenario, “2050 Whole”, the dataset was adapted as best as possible to the 2050 scenario found in the Energy Roadmap 2050.

The utilisation of the wind and solar plants decrease when the Renewable Energy Source(RES) capacities are increased to 2050 level compared to the 2030 base scenario. The main explanation to this is that the increased amount of RES gives more grid congestions, which limits the production. The other explanation is that the wind and solar potential actually exceeds the load for some hours. When the wind and solar power is increased to 2050 level the amount of fossil production strongly decrease, due to the higher marginal costs of fossil plants. This causes the share of renewable production to increase from 47% in the 2030 base scenario to 83% in the 2050 whole scenario. The highest concentration of renewable power is on the continent, especially in Germany. The flow on the HVDC cables goes from being mainly export from the Nordic countries and Great Britain to the continental countries in the 2030 base scenario to an increased amount of export from the continent in the “2050 Whole”. When the RES capacity is increased to 2050 level the total operating costs in the system goes down, due to the wind and solar power having zero marginal cost. The bottleneck cost become higher as the amount of RES is increased, implying that the grid becomes more congested. However it turns out that increasing the wind capacity alone, gives higher bottleneck cost than increasing both the wind and solar. This is because the solar power has a beneficial diurnal pattern, while the wind power has a

beneficial seasonal pattern. This means that the combination of wind and solar power follow the load pattern better than just the wind power and therefore causes less strain on the grid.

The fact that the utilisation of wind and solar strongly decrease and that the congestion costs become much higher in the 2050 scenario compared to the 2030 scenario implies that further grid reinforcements might be necessary if such high amounts of renewable power becomes a reality. The high variation in prices and exchange for some areas, that give a high strain on the grid, suggests that new storage possibilities should be investigated for the 2050 energy system.

Sammendrag

Den Europeiske Union(EU) har satt ambisiøse mål når det gjelder reduksjon i klimagassutslipp, målet er å redusere utslippene med minst 80-95% sammenlignet med 1990 nivå. Grunnet vanskeligheter med å eliminere alle utslipp i andre sektorer, som transport og landbruk, bør kraftsektoren være nært 100% fornybar. For det europeiske energisystemet betyr dette at mengden fossil kraft bør reduseres kraftig og at en stor mengde vind og solkraft må installeres fram mot 2050. Grunnet den lange levetiden til fossile kraftverk, er 2050 kun en investeringssyklus fram i tid. Det er derfor viktig at mulighetene og utfordringene som kan komme i et 2050 kraftsystem blir utforsket i dag.

I dokumentet Scenario Outlook and Adequacy Forecast(SO&AF), som utgis av the European Network of Transmission System Operators for Electricity(ENTSO-E) blir et scenario som gir installert kapasitet I hvert land i 2030 presentert. Energisystemet I 2030 blir også analysert i Twenties prosjektet utført av Sintef Energiforskning. I dokumentet «Energy Roadmap 2050» publisert av den europeiske kommisjon blir et scenario med en høy andel fornybar energi fram mot 2050 presentert. Hovedmålet med denne masteroppgaven er å analysere hvordan utviklingen av vind –og solkraft etter 2030 vil påvirke noen av hovedparameterne i kraftsystemet. Ett av fokusområdene er hvordan utnyttelsesgraden av vind –og solkraft vil endre seg når kapasitetene øker. Et annet fokusområde er hvordan den økte mengden vind og sol påvirker den termiske kraftproduksjonen, og hvordan produksjonsmiksen kan komme til å endre seg fra 2030 til 2050. Flyten i høyspent likestrøms korridorene og hvordan den økte mengden vind –og solkraft fram mot 2050 påvirker denne flyten er et annet viktig tema. Det siste temaet som blir behandlet i denne masteroppgaven er hvordan kostnadene og flaskehalskostnadene forandrer seg når produksjonssammensetningen forandres fra 2030 til 2050 nivå, spesielt hvordan vind –og solkraft påvirker flaskehalskostnadene separat og kombinert.

Denne studien ble utført ved å gjøre simuleringer med Power System Simulation Tool(PSST) modellen. De første simuleringene var med et grunnscenario, ved å bruke 2030 data fra SO&AF. Deretter ble simuleringer utført med vind –og solkapasiteter satt til 2050 nivå, separat og kombinert. Dette var for å vise virkningen vind –og solkraft har på de ulike parameterne i kraftsystemet. I det siste scenarioet, «2050 Whole» ble datasettet tilpasset så godt som mulig til 2050 scenarioet funnet i «Energy Roadmap 2050».

Utnyttelsesgraden av vind –og solkraftverk minker når kapasitetene med fornybar energi øker til 2050 nivå sammenlignet med grunnscenarioet for 2030. Hovedforklaringen på dette er at den økte mengden fornybar kapasitet fører til flere flaskehalser i nettet, som begrenser produksjonen. Den andre forklaringen er at vind –og solpotensialet til tider overstiger lasten. Når vind –og solkraft økes til 2050 nivå går produksjonen fra fossile kraftverk sterkt ned, dette er fordi fossile kraftverk har mye høyere marginalkostnader. Dette gjør at andelen produksjon fra fornybare energikilder øker fra 47% i 2030 grunnscenarioet til 83% i «2050 Whole». Den høyeste konsentrasjonen av fornybar kraft er på kontinentet, spesielt i Tyskland. Flyten i HVDC kablene går fra hovedsakelig å være eksport fra de nordiske landene og Storbritannia til kontinentet i 2030 grunnscenarioet til en økt mengde eksport fra kontinentet i «2050 Whole». Når kapasitetene til de fornybare energikildene økes til 2050 nivå synker driftskostnadene i systemet, siden vind –og solkraft har null marginalkostnad. Flaskehalskostnadene øker når den installerte kapasiteten med fornybar energi økes, noe som indikerer en høyere belastning på nettet. Det viser seg at å øke vindkapasiteten alene gir høyere flaskehalskostnader enn å øke vind og sol kombinert. Dette skyldes at solkraft har en fordelaktig døgnvariasjon mens vindkraft har en fordelaktig sesongvariasjon. Dette betyr at kombinasjonen av vind –og solkraft følger lastmønsteret bedre enn vindkraft alene og derfor gir mindre belastning på nettet.

At utnyttelsen av vind –og solkraft minker og at flaskehalskostnadene øker i 2050 scenarioet sammenlignet med 2030 scenarioet tyder på at videre nettutvikling kan være nødvendig hvis så store mengder fornybar energi blir virkelighet. Den høye variasjonen i priser og utveksling i noen områder, som gir en høy belastning på nettet, tyder på at nye energilagringsmetoder bør utforskes for energisystemet i 2050.

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First I would like to express my gratitude to my cosupervisor Magnus Korpås for his guidance and support throughout the process of writing this thesis. Magnus helped me to better understand the logic behind my results, and always shared his knowledge in a friendly and straightforward manner. A great thanks goes to Hossein Farahmand for helping me with the challenges I met with the simulation program. Hossein always made me feel welcome and helped me gain a lot of insight and overcome many of the challenges I met. Last but not least I would like to thank my husband Fredrik and my little son Johannes for keeping my spirits up with their good mood and positivity, and for reminding me that it is important to take the time to have fun, even in busy times.

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Abbreviations

Abbreviation	
GHG	Green House Gas
CCS	Carbon Capture and Storage
ETS	Emission Trading System
EU	European Union
CSP	Concentrated Solar Power
EC	European Council
RES	Renewable Energy Sources
EWEA	European Wind Energy Association
SO & AF	Scenario Outlook and Adequacy Forecast
ENTSO-E	European Network of Transmission System Operators for Electricity
TYNDP	Ten Year Network Development Plan
PSST	Power System Simulation Tool
PV	Photo Voltaic
OPF	Optimal Power Flow
DC	Direct Current
AC	Alternating Current
HVDC	High Voltage Direct Current
NTC	Net Transfer Capacity
EMPS	EFI`S Multi-area Power Market Simulator

Country code	
AT	Austria
BA	Bosnia-Herzegovina
BE	Belgium
BG	Bulgaria
CH	Switzerland
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GB	Great Britain
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IT	Italy
LT	Lithuania
LU	Luxembourg

LV	Latvia
MK	Macedonia
NI	Northern Ireland
NL	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
RU	Russia
SE	Sweden
SI	Slovenia
SK	Slovak Republic
UA	Ukraine

Table 1 Abbreviations

1 Introduction

The EU has set an ambitious goal of reducing the GHG emissions with at least 80-95% compared to 1990 levels within 2050. To achieve this, both ENTSO-E and the European Wind Energy Association (EWEA) states that the power sector should be close to 100% carbon emission free [1] [2]. To achieve this a much higher amount of renewable energy is necessary. Onshore wind is already one of the most mature renewable technologies and is expected to be an important part of the solution of achieving a higher amount of renewable energy towards 2050. Offshore wind is also expected to become more economically viable and the amount of offshore wind especially in the North Sea is expected to grow. Solar power is a more immature technology than wind power, but the learning curves will be steeper and it is very probable that solar power will be an important part of the European energy system in the future [2]. The Nordic countries has a lot of flexible hydro power that can help to balance the power system. However the potential for storable hydro is close to fully exploited and it is possible that more storage possibilities are needed in the future energy system.

This thesis starts with a 2030 base scenario, that is based on the generation capacities found in the Scenario Outlook and Adequacy forecast published by ENTSO-E [3]. The grid is the same as the first design step in the Split design found in the offshore grid report [4]. The geographical distribution of the generation capacities as well as the demand is from the 2030 dataset developed by SINTEF [5]. With this 2030 base scenario as a starting point this thesis aims at investigating the consequences of a large scale development of wind and solar power that can make the goal of reducing the GHG emissions with 80-95% a reality. The 2050 scenario that is used to develop the scenarios in this thesis is the 2050 high RES scenario found in the energy roadmap 2050 published by the ENTSO-E [2].

1.1 Problem definition

The main goal of this thesis is to answer how the further development of wind and solar after 2030 towards 2050 influence the main parameters in the power system.

- How is the utilisation of wind and solar influenced by the increased RES generation capacities towards 2050?
- How does the increased amount of RES influence the production of thermal power?
- How are the price levels in the different areas influenced?
- How does the increased amounts of wind and solar influence the flow in important corridors?
- How does the increased amounts of wind and solar influence the bottleneck costs?
- Is there need for more transmission capacity compared to the 2030 grid?
- How does the wind and solar production variation influence the total costs and the bottleneck costs?

1.2 Scope of the thesis

The scope of this thesis is to first put together a complete dataset for the 2030 scenario to implement in the PSST model. Then run simulations to find the result for 2030. After this the dataset should be modified so that the wind power is at 2050 level and simulations should be run so that the effect of the increased amount of wind power can be found. Then the same should be done for solar power. At last the 2030 dataset should be modified so that it matches the 2050 scenario as well as possible and new simulations should be run to investigate the grid parameters in a 2050 power system.

1.3 Outline

Chapter 2 is the background chapter giving all the relevant background and theory necessary to analyse the results from the simulations. Chapter 2 is called “The European Energy System in 2050”. It starts with presenting the European climate goals for 2050, followed by a section that presents different measures for achieving the 2050 goals. Here all the different scenarios found in the 2050 Energy Roadmap are presented with special focus on the high RES scenario that is chosen for this thesis. Next comes a presentation of the 2030 scenario that is an intermediate step towards reaching the 2050 goals. This section also includes a description of the grid design used.

Chapter 3 is the modelling chapter. The first section in this chapter includes a description of the PSST model, which is the simulation model used for all the simulations included in this thesis. The simulation procedure of the PSST model is described, followed by a description of the cost, load and generation modelling. The next section of chapter 3 describes the simulation structure. The scenarios that are included in the thesis are described, as well as the different simulations performed within each scenario. In the last two sections of chapter 3 the dataset for the 2030 and the 2050 scenarios are presented.

Chapter 4 is the most important chapter including the results of the simulations and an analysis of the results. The first section presents the results from simulations with the 2030 base scenario, and the most important results are analysed. The next sections presents the results from increasing the wind power to 2050 level and the effect of increasing the wind power on different parameters are analysed. The following section presents the results from increasing the solar power to 2050 level, focusing on the effect the increased solar power has on the grid. In the last section of this chapter the scenario that is adapted to fit the 2050 high RES scenario as well as possible is analysed.

Chapter 5 is the conclusion, that sum up the most important results found in chapter 4.

Chapter 6 presents the further work. This is research that is related to the topics discussed in this thesis, but is not investigated due to the scope of this study.

2 Background: The European energy system in 2050

In this chapter the background that is needed to understand and analyse the results found in the simulations described in chapter 4 is presented. Chapter 2.1 presents the goals for the 2050 energy system regarding GHG emissions, this is necessary to understand the implications this has on the production mix towards 2050. Chapter 2.2 presents the measures necessary to adapt the energy system towards 2050. It presents all the scenarios for the 2050 energy system given in the Energy Roadmap 2050. Chapter 2.3 presents the 2030 power system as it is given in the SO & AF. The 2030 scenario is an important stepping stone to achieve the goals for 2050.

2.1 Goals for the 2050 energy system: achieving 80-95% GHG emissions reduction compared to 1990 levels

The document that is used as a base for the modelling of the 2050 energy system in this work is the "Energy Roadmap 2050". It is an impact assessment and scenario analysis produced by the European commission. The Energy Roadmap 2050 proposes a number of scenarios and pathways for the 2050 energy system [2]. The number one driver behind the energy roadmap is the high GHG emissions in Europe today, and the fact that the great majority of such emissions are directly or indirectly linked to the energy sector. The energy roadmap works towards ambitious goals of GHG reductions towards 2050. The goals are based on the presidency conclusions of the European council in October 2009 [6]. The presidency conclusions states that all parties should embrace the goal of avoiding a temperature rise of more than 2 degrees Celsius to avoid dangerous impacts. This means that the global emission reductions should be at least 50 % and that the aggregate developed country reductions should be at least 80-95 percent compared to 1990 levels. The European council find it important that there should be established mid-term goals that are stepping stones towards the 2050 goal [6]

2.2 Measures for achieving GHG emission reductions

The general objective of the 2050 Energy Roadmap is to shape a vision and strategy of how the EU energy system can be decarbonized by 2050 while taking into account the security of supply and competitiveness objective of the EU.

A reduction of GHG emissions of 80-95 % is very high, and the reduction has to happen within less than 40 years. An important question is how this major reduction should be divided between the different energy sectors, and how much the power sector must reduce its emissions.

The Energy Roadmap presents five scenarios that all achieve at least 80 percent reduction in GHG emissions. A presentation of the scenarios follows. The scenarios are the Reference scenario, the Current Policy Initiatives scenario and five decarbonisation scenarios. The reference scenario is a projection, not a forecast, of developments in the absence of new policies beyond those adopted by March 2010. To take into account the developments between March 2010 and the time when the Energy Roadmap was published, the Current Policy Initiatives scenario was developed. However the focus in this work is on the five decarbonisation scenarios. All the decarbonisation scenarios assumes that the prices of oil, gas and coal will decrease towards 2050. This is because it assumes that global climate action will reduce the demand for fossil fuels and therefore cause the prices to decrease. A bit more about each of the decarbonisation scenarios are listed below

- The high energy efficiency scenario: This scenario aims at reaching close to 20 % energy savings by 2020, and pursue strong energy efficiency policies thereafter. Some of the measures to achieve this are summarized below.
  - New requirements for appliances
  - High renovation rates for existing buildings
  - All new houses after 2020 should comply with the passive house standard.
  - The utilities become obligated to achieve energy savings in their customers energy use.
  - Higher efficiency of power plants and less transmission and distribution losses.
  - Full roll-out of smart grids and smart metering.
  - More decentralized renewable generation.

- The diversified supply technologies scenario: This is a scenario that is mainly driven by carbon prices and carbon values. They are not a cost to the economic actors outside the EU Emission Trading System(ETS), but are economic drivers that change decision making. The carbon prices are applied to all sectors with GHG emissions. The main measures taken in this scenario is:

  - Carbon capture and storage (CCS) becomes a credible and commercially viable technology
  - There is confidence in nuclear power as a safe energy source.

- The High RES Scenario: The main goal of this scenario is to achieve a very high RES share and a RES share of about 90 percent in power generation. This is based on increasing the offshore wind power in the North Sea, installing significant amounts of Concentrated Solar Power(CSP) and storage development. A high amount of micro power generation is also assumed. This scenario has a much higher amount of installed renewable capacity than the other decarbonisation scenarios, and hence it is the most challenging scenario when it comes to storage and grid development. The policies and measures that are part of this scenario are as follows.

  - Facilitation and enabling policies, this includes lower lead times in construction and greater progress on learning curves based on higher production.
  - Market integration allowing for more RES trade
  - Stronger policy measures to achieve a high share of RES in overall energy consumption in particular in household micro power generation and increased production at the distribution level.
  - There should be a substantial increase in interconnections and Net Transfer Capacities, including DC lines from the North Sea to the centre of Europe.
  - Biomass and gas fired plants should work as back-up plants
  - There should be provided sufficient storage capacity through pumped hydro storage, CSP and hydrogen.
  - There should be demand side management, smart metering will allow consumers to turn off power during high price hours, this will reduce the need for storing variable RES electricity.

- Delayed CCS scenario: To achieve 80-95% reduction in GHG emissions the power sector has to be almost a hundred percent Carbon free, the inclusion of significant amounts of fossil fuel powered plants in the decarbonisation scenarios is only possible due to the use of Carbon Capture and storage. The delayed CCS scenario assumes that there is a delay in the development of CCS, reflecting acceptance difficulties regarding storage sites and transport. The following policies and measures are a part of this scenario:
  - Large scale development of CCS is only possible after 2040. This results in a delay in the learning curve for CCS and higher capital costs.
  - More nuclear in this scenario, because the acceptance of nuclear is high and the safety is considered adequate and waste issues are solved.

- Low nuclear scenario: This scenario shows the consequences of low public acceptance of nuclear power.
  - Due to the perceived risks of nuclear power plants in the aftermath of the Fukushima accident leads to cancellation of investment projects that are currently under consideration and no life time extension after 2030.
  - Fossil plants with CCS replaces the nuclear plants. There is a high confidence in CCS as a credible and commercially available technology. The acceptance of storage and CO2 networks is high.

    [6]

The high RES scenario is the scenario chosen for 2050 because the goal of this report is to investigate the effects of large amount of RES towards 2050.

The installed capacities in the 2050 high RES scenario is based on some technological assumptions, these assumptions are kept the same across all the decarbonisation scenarios so that the results more easily can be compared. The development of capital costs for different RES technologies from 2010 to 2050 is shown in the figure below.

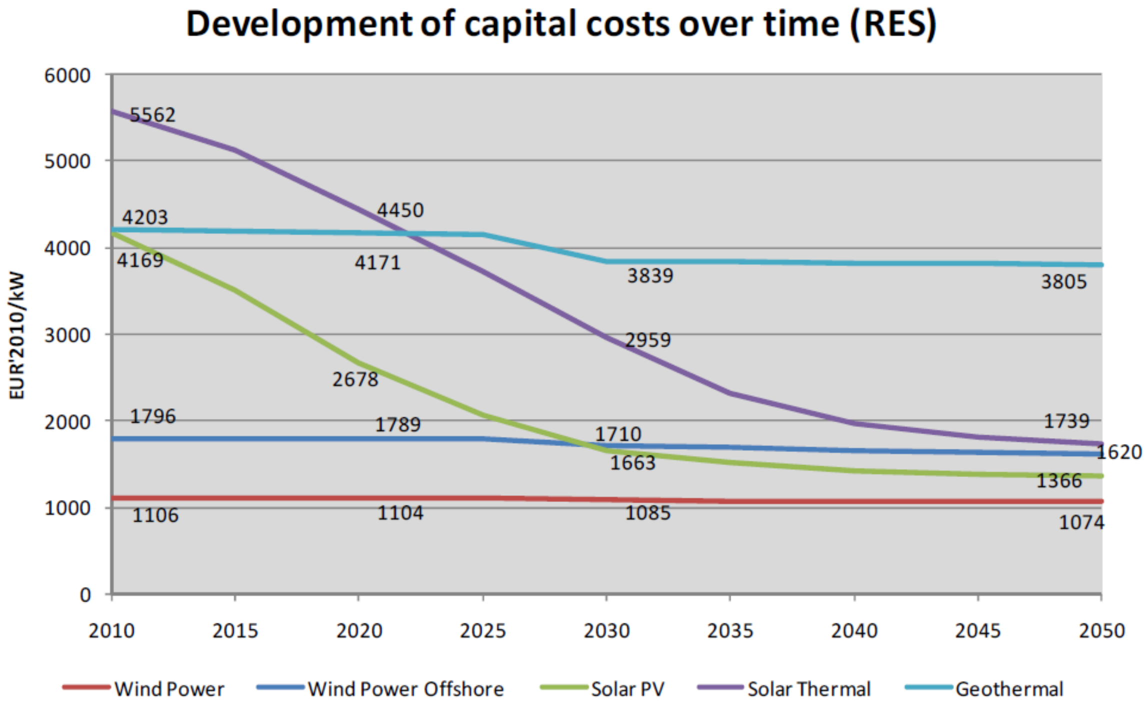


Figure 1 Development of capital costs of RES towards 2050 [6]

Figure 1 shows that the capital cost of onshore wind only decreases with a very small amount from 2010 to 2050. This is because onshore wind power is a mature technology and it is assumed that most of the possibilities for making this technology cheaper is already found. The price decrease of offshore wind is much higher than for onshore wind power. This is because the offshore wind power is a less mature technology and the learning curve is expected to be steeper. The highest reduction in capital cost is for Solar Thermal, which has a reduction in capital costs of 3823 Euro/kW. The second highest reduction in capital costs is for solar Photo Voltaic(PV), which has a reduction of 2803 Euro/kW from 2010 to 2050. These are both quite immature technologies today, and it is expected that the learning curves for these technologies are steep. It is worth noticing that it is assumed that the capital costs for solar PV becomes lower than for offshore wind around year 2030.

Next the installed capacities in all the European countries are shown as a percentage of the total installed capacity for the 2050 High RES scenario.

Production source	Percentage of installed capacity in the 2050 High RES scenario(%)
Wind	43.27
Solar	25.46
Hydro	10.15
Gas	8.36
Biomass	7.00
Coal	2.95
Nuclear	1.75
Oil	1.07

Table 2 Installed production capacity in the 2050 high RES scenario in percentage of installed capacity

The table shows that the wind is 43.27 percent of the installed capacity in the 2050 High RES scenario. It is left to see how much of the total production the wind will constitute in 2050. It is stated in the Energy Roadmap that this scenario will achieve 80-95 percent reduction in GHG emissions. According to the EWEA it would be difficult within the 2050 time frame to eliminate the emissions in sectors such as transport and agriculture. Therefore they claim that the achievement of the 2050 GHG emission reduction is only possible if the power sector emits zero carbon well before 2050 [1]. For the 2050 High RES scenario this means that if some of the production comes from fossil fuels this should be captured with the help of CCS.

It is about 36 years until 2050, and although this might seem far into the future, measures must be taken today for it to be possible to reach the 2050 goals. The lifetime of fossil fuel powered plants are long, 35 to 45 years for coal and 30 to 35 years for gas [1]. If the EU should reach for a hundred percent renewable power sector, this means that no new fossil fuel powered plants should be built after 2015.

2.3 2030: The intermediate step towards reaching the 2050 goals

In this work a base scenario for 2030 is used to model an intermediate stage towards 2050. The 2030 base scenario is based on a scenario found in the SO & AF. The SO & AF is an annual publication from ENTSO-E that presents the scenarios that are included in the ten-year network development plan(TYNDP). This publication includes a new element, namely two visions with qualitive data for 2030. These scenarios are meant to illustrate 2030 as an important stepping stone towards achieving the 2050 GHG emission reduction goal. Both of the two visions include a low market integration in Europe and are therefore based on national data. Vision 1 called “slow progress” assumes a general delay in achieving the 2050 energy roadmap goals. Vision 3 is constructed to be on track with these policy goals. Visions 2 and 4 are expected to be included in the TYNDP 2014 package and these two visions includes the effect of a strongly integrated market [3]. The vision 3 data is chosen for the 2030 scenario in this work, because the goal is to look at the effect of large amounts of wind power towards 2050, and this scenario assumes that the development is on track towards achieving the goals in the Energy roadmap 2050.

Of the data given for vision 3, it is only the generation capacities that is used for to create the 2030 base dataset. The load is not defined in the same manner as in PSST and cannot be used. The generation capacities in vision 3 is very important for this work, because there is a lack of national data for the 2050 scenario and it is therefore the national data given in vision 3 that is scaled up to fit the 2050 generation capacity level. The net generating capacity of vision 3 is assumed to have an annual growth of around 2.1%, corresponding to an annual load growth of between 1.1 and 1.3 percent.

In scenario vision 3 almost all countries are expected to increase their share of RES. The only exception is Switzerland and Lithuania that is expected to have a very slight decrease in RES capacity. The SO & AF assumes a growth of total installed RES capacity from 342 GW in 2013 to 560 GW in 2020. In vision 3 the goal is to reach the EU objectives for 2050. As a result of this, more than 200 GW of RES capacity is built between 2020 and 2030. The overall RES share for the ENTSO-E countries in the 2030 vision 3 is 54 percent. In the SO & AF there are two main observations regarding the development of RES capacity towards 2030. The first one is that there is a very rapid growth in installed wind capacity. The total wind capacity in the ENTSO-E countries is expected to grow from about 106 GW in 2013 to 344 GW in the 2030 vision 3. The second observation is that the relative share of hydro within RES is considerably reduced. The absolute hydro-values are unchanged, but with the high increase in other RES capacity the hydro constitutes a smaller share of the total RES capacity. This leads to new challenges in the power system since wind and solar do not have the same flexibility to balance the power system as many of the hydro plants do. The solar capacity is expected to grow from about 70 GW in 2013 to 200 GW in the 2030 vision 3 [3].

In the aftermath of the Fukushima accident in 2011 the decommissioning of nuclear power plants leads to nuclear share reductions from around 12% in 2013 to 7% in the 2030 vision 3 scenario. All nuclear plants in Germany are expected to be shut down as a reaction to the accident, so are all plants in Belgium due to a new law that states that all nuclear plants should be phased out. France derives over 75% of its electricity from nuclear energy today [7]. In the 2030 vision 3 this is decreased to a share of only 24%. Some of the Eastern European countries such as Slovenia, Hungary, Czech Republic and Bulgaria are expected to increase the share of nuclear power plants towards 2030 compared to todays level.

There is a general decreasing trend of fossil fuel based capacity towards 2030. The SO & AF assumes that the generation capacity of fossil fuel powered plants maintain until 2015, reaching a maximum level of 469 GW. In 2016 it is expected that the fossil fuel generation capacity starts to fall, reaching a capacity of 460 GW in 2020. The 2030 vision 3 expects no further fall in fossil fuel capacity and the generation capacity remains at 460 GW. In vision 3 there is a clear replacement trend of coal and oil by natural gas. One explanation to this may be the lower CO2 emissions of gas compared to coal and oil, in combination with a policy of higher CO2 costs. Another explanation might be that gas plants are more suitable as back-up plants for variable RES production due to the short response time.

For the purpose of this work the capacities of the power plants in the existing model was adjusted to fit the 2030 vision 3 as good as possible, the resulting share each generation type has of the total generation capacity is shown in the table below.

Production Source	Percentage of installed capacity(%)
Wind	24.78
Solar	14.54
Hydro	16.97
Gas	20.33
Biomass	3.89
Coal	8.53
Nuclear	7.63
Oil	2.99

Table 3 Installed production capacity in the 2030 Base scenario in percentage of installed capacity

The overall share of RES, fossil and nuclear is a bit different from what was given in the 2030 vision 3 due to some small modifications to fit the existing power plants, but the share was in the same range.

2.3.1 The grid

The grid used in this work is produced under the offshore grid project [4]. In the following a short description of how the grid is designed is given.

In the study of how to connect the offshore wind farms to shore the offshore grid report concludes that it is often beneficial to connect wind farms close to each other to one hub forming only one transmission line to shore. Connecting the offshore wind farms to one hub where it is beneficial constitutes the first step in the grid design. The first step is called the hub base scenario. In the second step two interconnected grid designs were proposed, the direct design and the split design. In the direct design only direct interconnections between countries are investigated. The split design is different because it designs an offshore grid around the planned offshore wind farms, this means that for some of the larger wind farms the connections are split between countries. The offshore grid report concludes that both designs are highly beneficial, but that the split design is slightly more cost effective than the direct design. The offshore grid report also presents a step 3 which includes meshed connections. A short explanation of each step in the split design follows.

Step 1) Based on price differences between countries direct interconnections were constructed and split wind farm connections were considered where it was possible. As a result of step one beneficial direct interconnectors and split wind farm connections were obtained

Step 2) Beneficial hub to hub and tee-in connections were considered

Step 3) Beneficial meshed connections were identified.

In the grid that is used in this work the Hub-to-hub and Tee-in(step 2) is not included and the Meshed interconnectors(step 3) is not included. The reason why only step one is included is that the grid including the meshed interconnectors and the Hub-to-Hub and Tee-in connections this is a special case and it is uncertain what kind of offshore grid that will be built in the future. This depends on many factors such as economic development and market integration between countries. Using the grid design that includes meshed connections would also make it more complicated to draw conclusions of how the exchange between countries would develop.

The map below shows the offshore grid that is used in this work.

Figure 2 Grid design used in this thesis

An example of a split connection is between Sweden and Poland where there are two split connections built around two large offshore wind farms. Another split connection can also be found between Great Britain and Belgium. Some of the countries are connected through one single HVDC cable, while others such as Great Britain and France are connected through several cables. The map shows that there are three offshore wind farms outside Norway, these are called Ægir, Idunn and Sørlige Nordsjøen. These are included in the 2050 scenarios, but not in the 2030 scenario.

3 Modelling

3.1 PSST

Power System Simulation tool (PSST) is developed by Sintef Energy Research, and is further adapted and developed under the Tradewind project [8]. It is programmed in Matlab using the Matpower functionality and runs an Optimal Power Flow (OPF) problem for a given power system model for each hour of the year. The PSST uses a DC power flow formulation to represent the whole continental European transmission system, in this system there are five grid models representing different synchronous systems. The synchronous systems are the Nordic region, the RG continental European region, Great Britain, Ireland and the Baltic region [9]. The grid models are the same as those used in the Tradewind project. The RG continental European system was created by the team of prof Janusz Bialek at the university of Edinburgh which covers the former UCTE synchronous zone and is based on publicly available data.

The PSST model is a flow based model that uses nodal pricing. Nodal pricing is a method of determining the market price in each node. A node represents a physical location in the transmission system where energy is injected by generators or withdrawn by loads. Unlike the area price model that is used in the Nordic power system, where the price is settled by an implicit auction. This means that different area prices are calculated if the need for exchange between areas exceeds the transmission capacity. Only the total demand for exchange to or from an area is taken into consideration, not the real physical flow that is a consequence of the different area prices. The nodal pricing gives the real price in each node, taking losses and transmission congestions within zones into account. Meaning that the nodal price consists of three elements, the marginal cost of generation, the marginal cost of losses and the marginal cost of transmission congestions [10] [11].

Next the simulation process of the PSST model is shown.

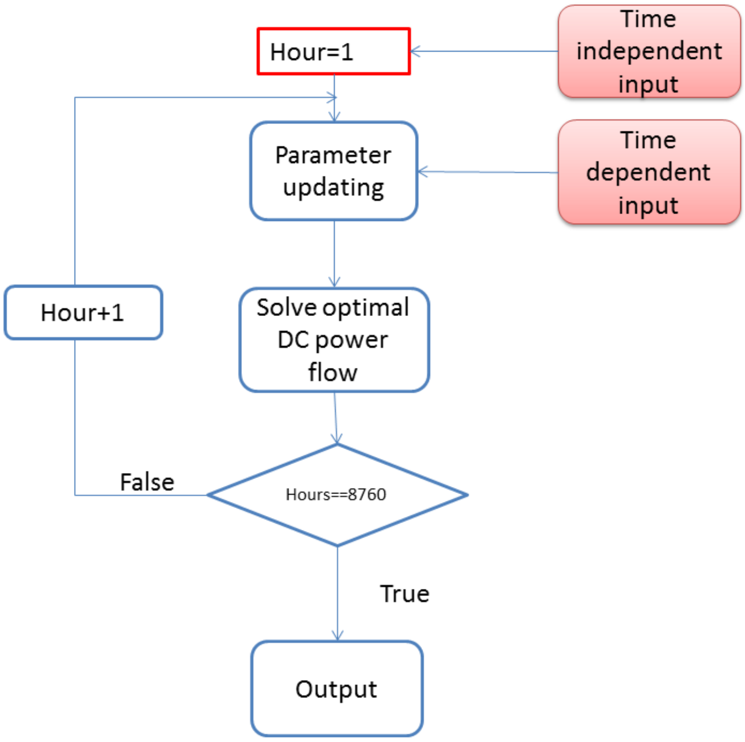


Figure 3 Simulation process of the PSST model [8]

The PSST model runs a DC optimal power flow for each hour that is simulated, for example if the user wish to simulate a whole year the number of hours is set to 8760. For each hour input is fed into the model, some of the parameters in the model are time dependent and are updated every hour, while others are constant for all the year. For each hour the model runs a DC optimal power flow, until the number of hours reaches 8760, when the results can be presented. In the DC Optimal Power Flow the goal is to minimize the total generating. DC optimal power flow is a way of solving an optimization problem in a simplified manner so that less time and computational power is needed. The free variables in the DC OPF in PSST are the power output of all generators and the flow on HVDC interconnections. This means that the model finds optimal generation and optimal HVDC flow [8]. The cost modelling in PSST is treated in the section below. Section 2.1.2 and 2.13 treats the load and generation input to the model.

3.1.1 Cost modelling

The cost function used in the PSST model is described in the Tradewind report [8]. The total cost is given as either a linear, piecewise linear or a quadratic function depending on the generator type. These three cost functions are shown in the graphs below.

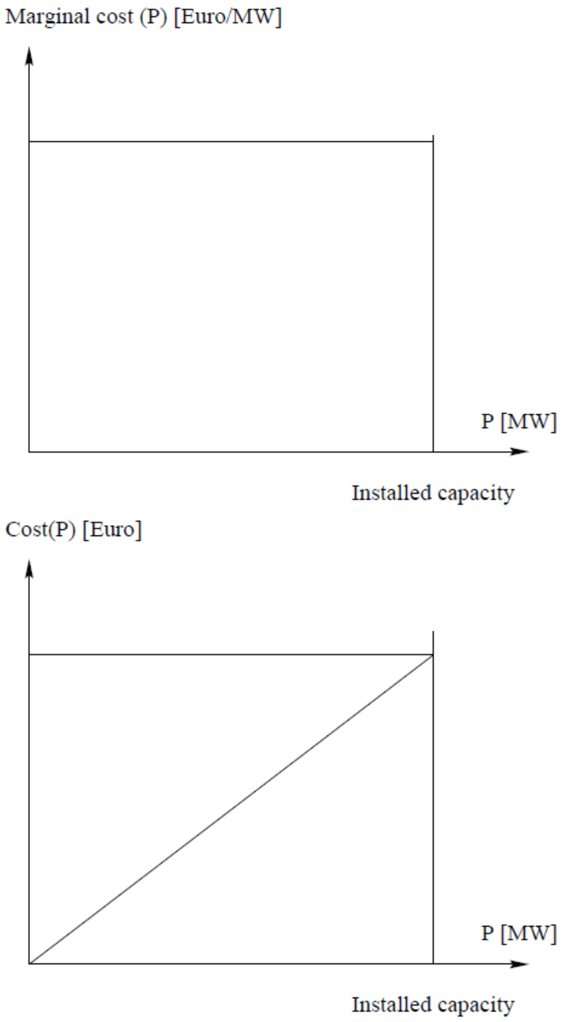


Figure 4 Marginal cost and cost, linear cost function

The generators that has a linear cost function has the same marginal cost for all production volumes. Linear cost functions are seldom used because most generators have an increase in marginal cost as the production volume increases.

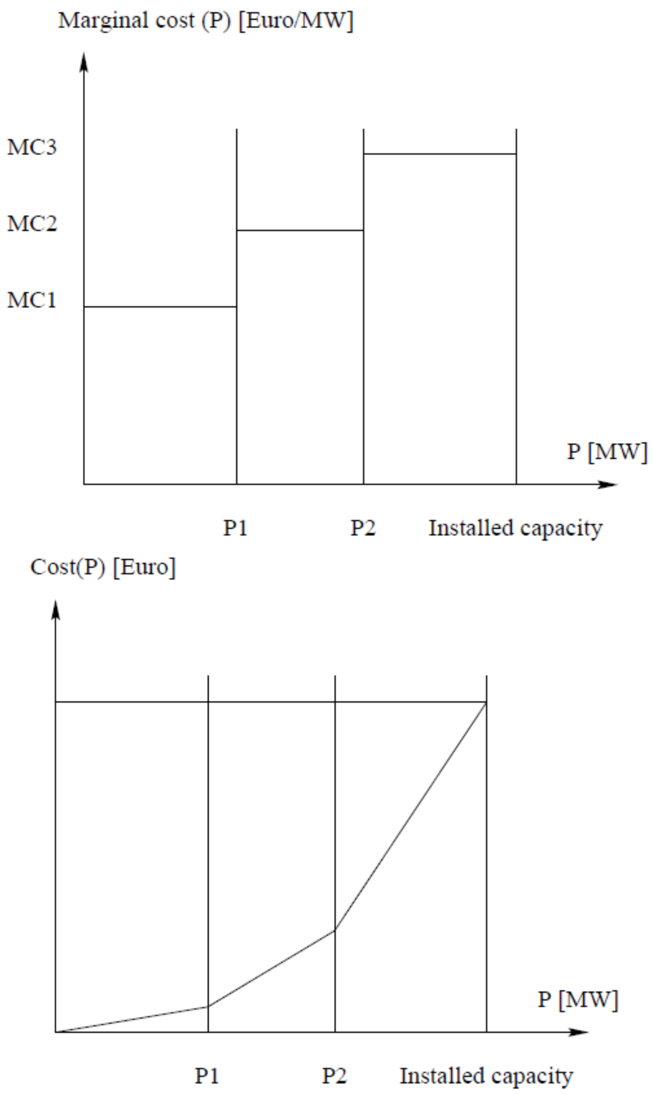


Figure 5 Marginal cost and cost of piecewise linear function

As is shown in Figure 5 a generator with a piecewise linear cost function consists of several marginal costs. The thermal plants usually have a piecewise cost function because the marginal cost usually increase with production volume.

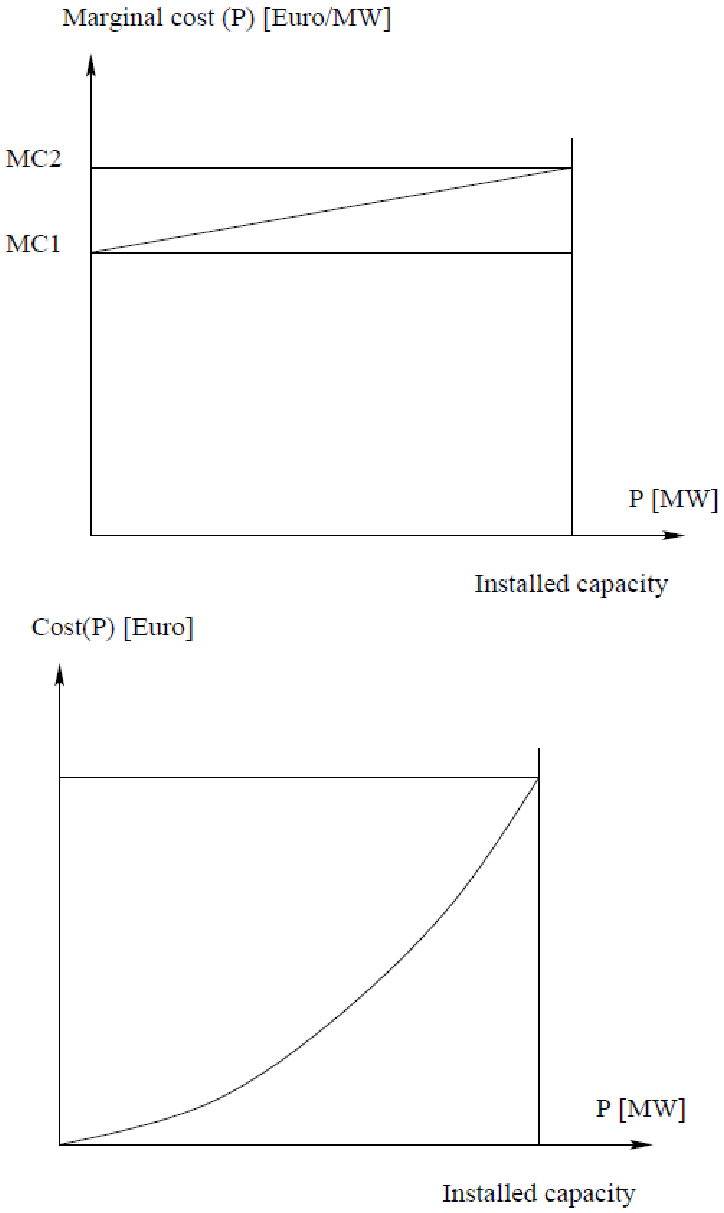


Figure 6 Marginal cost and cost of quadratic function

The hydro generators use a quadratic cost function. The reason for this is that the marginal cost of hydro(the water value) is strongly influenced by the hydro production. When the water value is slightly lower than the system price the hydro plant would produce at maximum, this will lead to lower reservoir level and the water value quickly decrease. When the water value becomes lower than the system price the production comes to a complete stop. This will give a very unstable and unwanted production pattern of hydro power. To avoid this the hydro generators have quadratic cost functions as shown in Figure 6.

As mentioned earlier the goal of the optimisation procedure is to minimize the generation cost. The linear optimisation problem is shown in the equation below

$$\min F = \sum_{i=1}^{Ng} C_i \times P_i^G + \sum_{i=1}^{Nb} C^{Rat} \times P_i^L$$

F=Objective function

Ng=Number of generators

Nb=Number of buses

C_i=Marginal generation cost at bus i

P_i^G=Generated active power at bus i(MWh)

C^{Rat}=Rationing cost(Euro/MWh)

P_i^L=Active power consumption at bus i

The objective function of minimizing the total generation costs is also subject to a number of constraints, including the transmission limits on AC and HVDC lines, the energy balance at each bus, the power generation limits between the minimum and maximum production and limits on the flow between different market areas through the Net Transfer Capacities(NTCs).

In addition to the sum of the costs at each generation node the objective function minimize the rationing cost of energy not supplied. Load rationing happens in situations when the supply is lower than the demand in an area. In some cases the supply might be higher than the demand, in these situations the model implements a simple form of load shedding. Load shedding is the ability to reduce demand. The cost of reducing the demand is the rationing cost and it must always be higher than the cost of the most expensive generator. If the rationing price is lower than the cost of the most expensive generator the model will implement load shedding before producing from the most expensive generator [12].

Each generation source have different marginal cost, the wind and solar power has zero marginal cost. The order of the marginal cost of the different thermal sources are listed below, starting with the source with lowest marginal cost.

1. Nuclear
2. Renewable other than wind(Biomass)
3. Lignite coal
4. Hard coal
5. Gas
6. Oil
7. Mixed fuels Oil/Gas

The thermal plants with low marginal cost are typically used to serve the base load, nuclear is a typical example of this, with low marginal cost and long reaction time when it comes to stepping up or down the production. The gas and oil plants are typically used to serve the peak load and can be useful to cover periods with high load and low wind production, the marginal costs of these plants are high and the ability to step up and down production fast is good.

3.1.2 Load input

The load data is given by the annual demand for each area and the load profile for each area. The load profile gives the hour-by-hour distribution of demand. The load data from 2006 are used as reference and is scaled up using the relative increase/decrease in load.

3.1.3 Generation input

The generation data contains type definitions of the various generators found in the model, for example, hydro, nuclear, oil and wind. It also contains information on generation capacities and marginal costs for each generator type.

Thermal

The thermal power plants consists of several types with different marginal costs, these are hard-coal, lignite-coal, oil, oil and gas, gas, biomass and nuclear. Lignite coal and nuclear have low marginal costs and are typical base load plants. Oil and gas plants are typical peak load plants because they can be regulated fast up and down and how higher marginal costs.

Hydro

The hydro input consists of three files, one called hydro data which gives information on the reservoir capacity, the pumping capacity, start reservoir and annual inflow. The two other files are imported from another model called the EMPS model, and contain the water inflow and the water values. The water inflow from the EMPS model is scaled according to the total annual inflow given in the hydro data file.

Wind

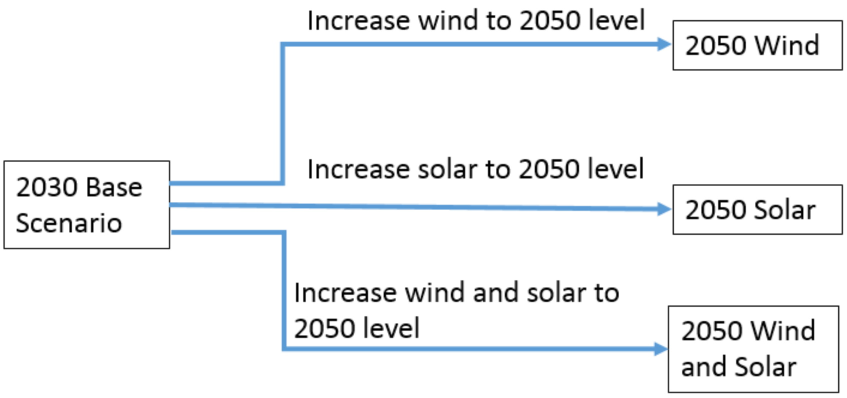
The wind power is given as a wind power time series. The wind power time series consists of one capacity vector including the capacities of all wind power plants and one wind potential matrix giving the relative wind potential production for each power plant for each hour of the year. Multiplying the wind capacity vector and the wind potential matrix gives the absolute wind power potential.

Solar

The solar is also given as a time series, which is from the COSMO model [13].The solar time series is a matrix giving the absolute solar potential for each hour of the year for each solar power plant. The solar time series does not include a capacity vector like the wind power time series.

3.2 Simulation structure

The first simulation set is the 2030 base scenario which use data that is adapted to the visions for 2030. To see how increased amounts of renewable energy towards 2050 affects the system, three new scenarios are developed. In the 2050 wind scenario only the wind power is increased to 2050 level, in the 2050 solar scenario only the solar is increased to 2050 level in the 2050 wind and solar scenario both the wind and solar capacities are increased to 2050 level. These four scenarios and their structure are illustrated in the figure below.



One final scenario is also simulated, this is the 2050 whole scenario. In this scenario the goal is to fully represent the 2050 energy system. In this scenario the thermal power is adapted in addition to the wind and solar capacities.

Several simulations are done for each scenario to investigate the congestion costs. The goal of performing these simulation is to look at how increased amounts of wind and solar towards 2050 influence different parameters in the energy system. For example the utilisation of wind and solar, the need for and utilisation of thermal power plants, the important flows in the grid, congestions in the grid and the need for improvement of the grid towards 2050 if a high amount of wind and solar production is installed. To investigate how the wind and solar production influence the congestion costs of the grid, different sets of simulations are performed for all the scenarios. First the simulation sets performed in the 2030 base scenario and the 2050 whole scenario are explained.

The first set of simulations are performed to find the effect the wind power has on the bottleneck cost. This is done by first finding the total bottleneck cost for a whole year with wind power and then finding the total bottleneck cost for the same system with the wind power capacity set to zero. Then the bottleneck costs without wind power is subtracted from the bottleneck costs with wind power to find the contribution of wind power to the bottleneck cost. The bottleneck cost are found by first doing a simulation with limited grid and then with infinite grid. The simulations with limited grid are done with limitations on transmission on the HVDC corridors and on the AC corridors between countries. The internal limitations within countries are not included apart for some limitations on the grid inside Norway. In the infinite grid simulations the grid is as close to infinite as possible, with the capacities on the HVDC connections set to a very high value and the transmission on the AC corridors set to infinite. Below all the simulations done for the 2050 whole and the 2030 base scenario are shown.

Simulations with wind power
Total annual cost With limited grid(Euro/MWh)
÷ Total annual cost with infinite grid(Euro/MWh)
= Bottleneck cost with wind power(Euro/MWh)

Simulations without wind power
Total annual cost With limited grid(Euro/MWh)
÷ Total annual cost with infinite grid(Euro/MWh)
= Bottleneck cost without wind power(Euro/MWh)

Δ Bottleneck costs

Table 4 Bottleneck costs due to wind power

The next simulation set that is performed is to investigate how the variability of wind influence the bottleneck costs. This is done by performing simulations with the wind potential throughout the whole year set equal to the average wind potential.

Simulations with wind power
Total annual cost With limited grid(Euro/MWh)
÷ Total annual cost with infinite grid(Euro/MWh)
= Bottleneck cost with wind power(Euro/MWh)

Simulations with constant wind power
Total annual cost With limited grid(Euro/MWh)
÷ Total annual cost with infinite grid(Euro/MWh)
= Bottleneck cost with constant wind power(Euro/MWh)

Δ Bottleneck costs

Table 5 Bottleneck costs due to variations in wind power

Then the same sets of simulations are performed to find the effect the solar has on the bottleneck costs this is shown in the table below.

Simulations with solar power
Total annual cost with limited grid
÷ Total annual cost with infinite grid
= Bottleneck cost with solar power
Simulations without solar power
Total annual cost with limited grid
÷ Total annual cost with infinite grid
= Bottleneck cost without solar power
Δ Bottleneck costs

Table 6 Bottleneck costs due to solar power

The next set of simulations performed is to find how the variability of solar power influence the bottleneck costs. This is done by running simulations with the solar potential at each solar plant set equal to the average solar potential throughout the whole year.

Simulations with solar power
Total annual cost with limited grid
÷ Total annual cost with infinite grid
Bottleneck cost with solar power
Simulations with constant solar power
Total annual cost with limited grid
÷ Total annual cost with infinite grid
Bottleneck cost with constant solar power
Δ Bottleneck costs

Table 7 Bottleneck costs due to variations in solar power

The effect of having both constant wind production and constant solar production was found in the following manner.

Simulations with wind and solar power
Total annual cost with limited grid
÷ Total annual cost with infinite grid
= Bottleneck cost with wind and solar power
Simulations with constant wind and solar power
Total annual cost with limited grid
÷ Total annual cost with infinite grid
= Bottleneck cost with constant wind and solar power
Δ Bottleneck costs

Table 8 Bottleneck costs due to variations in wind and solar power

These simulations were performed for the 2050 whole scenario and the 2030 base scenario. The simulations with variable solar and with variable wind is the same simulation with both wind and solar being variable. For the 2050 wind, the 2050 solar and the 2050 wind and solar there is fewer simulations performed for each scenario. These are shown below.

2050 Wind
-simulations with wind set to 2050 level with limited grid
-simulations with wind set to 2050 level with infinite grid
-simulations with constant wind set to 2050 level with limited grid
-simulations with constant wind set to 2050 level with infinite grid

2050 Solar
-simulations with solar set to 2050 level with limited grid
-simulations with solar set to 2050 level with infinite grid
-simulations with constant solar set to 2050 level with limited grid
-simulations with constant solar set to 2050 level with infinite grid

2050 wind and solar
-simulations with wind and solar set to 2050 level with limited grid
-simulations with wind and solar set to 2050 level with infinite grid
-simulations with constant wind and solar set to 2050 level with limited grid
-simulations with constant wind and solar set to 2050 level with infinite grid

Table 9 Simulations for 2050 wind, 2050 solar and 2050 wind and solar

These simulations make it possible to investigate the effect the wind has on the bottleneck costs when the wind power capacity is increased to 2050 level and the effect of the variability of wind on the bottleneck costs when the wind capacity is increased to 2050 level. The same is true for the solar power. The simulations with the 2050 wind and solar scenario shows the combined effect of increasing both these capacities to 2050 level.

3.3 Data for 2030

In this section the data set that is used for the 2030 base scenario is presented. As mentioned in section 2.3 the 2030 scenario is based on the data found in the SO & AF published by ENTSO-E [3]. The adaption of the different parameters to fit this scenario is discussed in the following section.

3.3.1 2030 generation capacities

The installed wind power capacity is found from the SO&AF scenario vision 3 dataset for each country. The geographical distribution and the variation of wind power with time is from the original dataset provided by Sintef [5]. This is the best approximation because there is no information about the individual generators in each country in the SO&AF. The codes used to scale the capacity of each wind generator to match the capacity in SO&AF can be found in appendix A.1 .

In the SO&AF a distinction was made between offshore and onshore wind power plants. Therefore the capacities of the wind farms located offshore were scaled with a different factor than those located onshore. The original wind production had to be manipulated to fit the 2030 ENTSO-E scenario. The windpower time series consists of capacities at each wind node, and the variation of wind power throughout a year at each wind node. When multiplying these, the real wind potential at a given node is found. To change these into the ENTSO-E cacpacities shown in the table above the capacities belonging to each country were summarized and were scaled to fit the ENTSO-E values.

The solar power data is called Cosmo solar time series for 2030 and only consists of the name of the solar nodes and the actual solar potential throughout a year at each node. The same strategy was used to find the new solar time series except that the capacity at a given node were defined as the maximum output of the solar potential.

All generator capacities are adapted to the SO&AF vision 3, however sometimes approximations are made, for example if a certain generation type is non-existent in the old dataset.

The countries of main interest are those with the most renewable energy. The generation mix for these countries are listed below.

- Germany has 85 GW of installed wind power which is higher than any of the other European countries, Germany also has a high amount of fossil fuel powered plants which amounts to 77 GW, in addition to 69 GW of solar power. This makes Germany the country with the most variable renewable production.
- Spain is the country with the second most wind, with an installed capacity of 48 GW. The highest share of the installed capacity in Spain comes from gas plants, with an installed capacity of 52.9 GW. Spain also has a substantial amount of both solar and hydro of about 25 GW each.
- Great Britain has 47 GW installed wind power, 46 GW from fossil fuels and 13.9 GW from nuclear. In addition to a small amount of installed hydro and biomass.
- France has 40 GW of wind power and 40 GW of nuclear power in addition to 22 GW of fossil fuel and 30 GW of solar. This means that France has 70 GW of variable power production.
- Italy like many of the other continental countries has a combination of fossil fuel and renewable power production. Italy has 15.7 GW of installed wind power, 42 GW solar and 22 GW of hydro. The installed fossil fuel plant capacity is 65.4 GW.
- In the Netherlands most of the production comes from wind, solar and gas. With an installed wind power capacity of 12 GW, 8 GW of solar capacity and 21 GW of gas capacity.
- The biggest part of the installed capacities in Sweden comes from hydro, wind and nuclear. With an installed hydro capacity of 16.2 GW, 11.1 GW of wind and 10 GW of nuclear.
- In Denmark most of the installed capacity are wind, solar and biomass. The installed wind power is 10.46 GW, the installed solar is 3 GW and the biomass is 4.16 GW.
- Poland produces most of the power from wind, fossil fuel powered plants and from nuclear. The installed wind power capacity is 10 GW, the fossil fuel power installed is 28.2 GW and the nuclear is 6 GW.
- Belgium has most of its production from wind, gas and solar plants. The installed wind power capacity is 8.54 GW, gas is 15.6 GW and solar is 5.7 GW.
- Norway is supplied only by wind and hydro and is the country in Europe with the highest amount of installed flexible hydro power. The installed hydro is 31.4 GW and the installed wind is 4.8 GW.

Some main characteristics of the European capacity mix can be drawn from the information above. The central European countries like Germany, France, Netherlands and Belgium has a high amount of wind and solar capacity in combination with fossil fuel powered plants. Norway and Sweden has the highest share of installed capacity from flexible hydro power plants. Great Britain has a very high percentage of wind power, but almost the same capacity from fossil fuels.

Since the main focus in this work is on wind and solar production the installed wind and solar capacities for all the European countries are shown below, with the countries with the highest combined wind and solar capacities in 2030 at the top of the table.

Country	Onshore Wind (GW)	Offshore Wind(GW)	Sum Wind(GW)	Solar(GW)	Sum wind and solar(GW)
'DE'	61.40	23.60	85.00	68.80	153.80
'ES'	46.10	1.90	48.00	24.30	72.30
'FR'	28.00	12.00	40.00	30.00	70.00
'IT'	14.20	1.50	15.70	42.00	57.70
'GB'	11.07	35.91	46.98	0.01	46.99
'NL'	6.00	6.00	12.00	8.00	20.00
'BE'	4.54	4.00	8.54	5.74	14.28
'DK'	5.92	4.54	10.46	3.00	13.46
'GR'	7.50	0.00	7.50	5.30	12.80
'SE'	10.00	1.10	11.10	1.00	12.10
'PL'	7.30	2.70	10.00	1.00	11.00
'AT'	5.50	0.00	5.50	3.50	9.00
'BG'	4.00	0.00	4.00	3.50	7.50
'PT'	6.34	0.00	6.34	0.72	7.06
'RO'	5.50	0.00	5.50	0.65	6.15
'IE'	5.20	0.50	5.70	0.05	5.75
'FI'	2.55	2.35	4.90	0.04	4.94
'NO'	4.80	0.00	4.80	0.00	4.80
'CZ'	1.40	0.00	1.40	2.10	3.50
'NI'	2.23	0.00	2.23	0.00	2.23
'HR'	1.50	0.00	1.50	0.00	1.50
'LV'	0.00	1.48	1.48	0.02	1.50
'SI'	0.24	0.00	0.24	1.12	1.36
'HU'	1.00	0.00	1.00	0.20	1.20
'SK'	0.45	0.00	0.45	0.72	1.17
'LT'	1.00	0.00	1.00	0.02	1.02
'RS'	1.00	0.00	1.00	0.00	1.00
'EE'	0.65	0.25	0.90	0.10	1.00
'CH'	0.90	0.00	0.90	0.00	0.90
'LU'	0.13	0.00	0.13	0.07	0.20
'BA'	0.00	0.00	0.00	0.00	0.00
'UA'	0.00	0.00	0.00	0.00	0.00
'MK'	0.00	0.00	0.00	0.00	0.00
'RU'	0.00	0.00	0.00	0.00	0.00
Sum	246.42	97.83	344.25	201.96	546.21

Table 10 Wind and solar capacities 2030

Next the total installed generation mix for Europe in the 2030 scenario is shown in a column diagram.

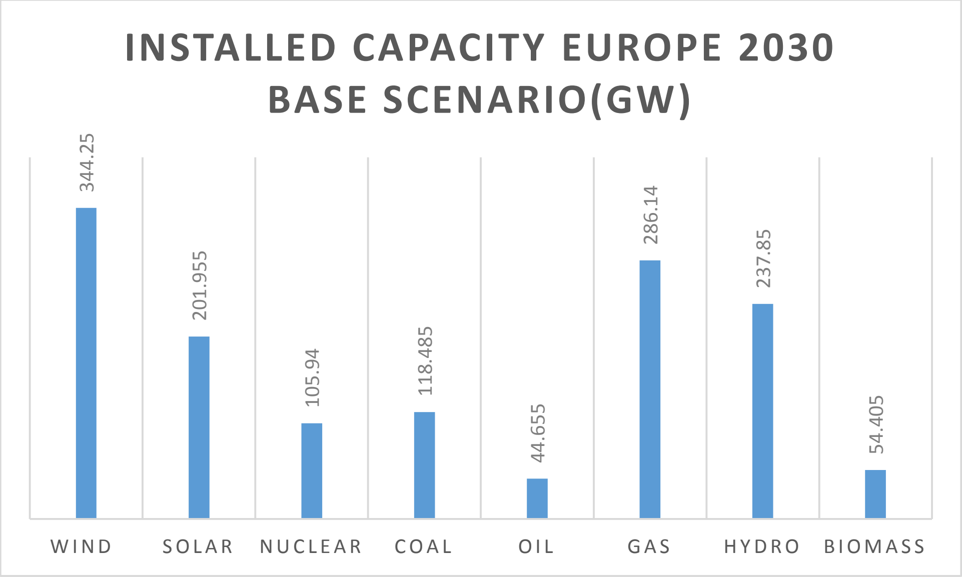


Figure 7 Capacity mix in the 2030 base scenario

The figure shows that the highest installed capacity is wind, with a total capacity of 344.25 GW, there is also a high amount of hydro and solar. The installed hydro includes both storable and run of river hydro. There is still a substantial amount of installed fossil power, the highest amount being in gas plants. Combined, the amount of installed fossil is 449.28 GW. The total amount of renewable power is 838.46 GW. There is 1.87 times more installed renewable power than there is fossil power. However it is important to remember that the utilisation time of wind and solar is much lower than for the fossil plants that theoretically could produce a hundred percent at all times.

3.3.2 Demand

The demand is given in hourly load profiles in addition to an annual demand. The load profiles are scaled according to the annual demand. The choice is made to not scale the demand to fit the SO& AF scenario because the load is given in a very different manner in the SO & AF, where it is given as total load at two different times of the year for each country. The annual demand used is the same as the demand used in the Twenties report and are shown in the table below [12].

Area	2030
AT	76.38
BA	16.5
BE	114.744
BG	39.48
CH	75.2
CZ	86.68
DE	678.48
DK	41.644
EE	10.66
ES	406.56

FI	93.263
FR	604.12
GB	399
GR	86.7
HR	25.25
HU	51.94
IE	38.46
IT	436.41
LT	13.49
LU	6.99
LV	4.45
MK	7.7
NL	125.28
NO	114.89
PL	187.83
PT	70.32
RO	71.21
RS	45.01
RU	55.0128
SE	155.911
SI	18.22
SK	41.16
UA	4.2
NI	9.7
AL	0
ME	0

Table 11 Demand

The table shows that the countries with highest demand are Germany with 678.48 TWh, then comes France with 604.12 TWh, then Italy with 436.41 TWh, then Spain with 406.56 TWh. It is no doubt that the demand centre is located in the continental Europe. Looking at the Nordic countries and also Great Britain the demand is much lower.

3.3.3 Net Transfer Capacities

The Net Transfer Capacities(NTC) values between the countries are ignored in the simulations in this work, because these would set limitations on the flow between countries and in this work the focus is on recognizing these flows as a consequence of generation capacity and grid limitations not based on external trading limits.

3.4 Data for 2050

In this section the generation capacities for 2050 are presented. These are found in the Energy Roadmap 2050 [2]. The demand is not changed because there was no data in the 2030 base scenario that could be used, and the difference between the 2050 high scenario and the demand used in the 2030 base scenario was acceptable. The total demand for the 2050 high scenario was 3377 TWh while the total demand for the 2030 base scenario was 3859. The choice is made to keep the demand in the original dataset [5].

3.4.1 Generation capacities in the 2050 scenario

In this chapter the adaption of the generation capacities from the 2030 scenario to the 2050 scenario is explained. The 2050 wind and solar time series are scaled from 2030 level to fit the capacities given in the 2050 energy roadmap [2]. How this is done is explained later in this section. For the 2050 whole scenario the nuclear and thermal power is scaled as well.

The installed hydro power is not changed compared to the installed hydro in the 2030 base scenario. This is because the data in the 2050 energy roadmap is only given for the EU, and Norway and Switzerland have a high amount of hydro and they are not a part of the EU. In addition the Energy Roadmap assumes a lower amount of installed hydro than the data used in 2030 for the EU, and it is regarded as unlikely that the amount of installed hydro will decrease.

Scaling of the wind power time series

The total onshore and offshore wind power for 2030 are found for the EU 27 countries, then this is compared to the 2050 total installed onshore and offshore wind power and one scaling factor are found for onshore and one for offshore wind power. These scaling factors are applied to all the countries included in the PSST model. The scaling factor for onshore capacity is 2.59 and the scaling factor for offshore capacity is 3.82. This scaling leads to an increase in total installed wind power capacity in Europe from 344.25 GW in 2030 to 1024.9 GW in 2050. The installed wind power capacity of 1024.9 GW is found by scaling the total amount of wind power for the EU 27 countries in 2030 up to 984 GW in 2050. The same scaling factor is used for all the European countries, also those not members of the EU. According to the Energy Roadmap this should lead to wind supplying 48.7 % of the electricity demand in 2050.

According to the SO & AF Norway will have no offshore wind in 2030. The 2050 Energy Roadmap assumes that all the potential for offshore wind power in the North Sea is fully exploited. Therefore three offshore wind farms in Norway that were not part of the dataset in 2030 is included for the 2050 scenario. The wind power time series for these wind farms were found in the original PSST dataset [5].

The 2030 wind power time series included in PSST consists of a capacity vector and a vector that shows the variation of wind power throughout the year. When scaling the wind power up to 2050 level only the capacity vector is changed. This consists of the capacity of the 892 generators included in the model. These generators are divided into onshore and offshore generators and multiplied with 2.59 if it is an onshore wind farm and with 3.82 if it is an offshore wind farm.

Simulations were also made with constant wind power. This was done by finding the average wind potential at each wind node, and then setting the wind potential equal to these values for the entire year. The codes for scaling the wind power time series to 2050 level is shown in the appendix A.3.

Scaling of the solar time series

The solar time series is a bit different because it is only given by its potential production for each hour of the year for each bus, so the solar time series is represented by its actual potential and not by its capacity and variation throughout a year like the wind power time series. The increase of solar power is about 400 GW from 201 GW in 2030 to 603 GW in 2050. The solar time series are scaled by finding the maximum solar potential for each node and then using that as the solar capacity at the given node.

Scaling of nuclear and fossil fuel

The total amount of coal in the EU-27 countries for the 2030 scenario was 104.98 GW. In the 2050 scenario this is reduced to 62 GW. From this a scaling factor is found and the 2050 coal capacity is set to be about 60 percent of the 2030 capacity. The 2050 scenario gives only one number for coal capacity while in PSST there is both lignite coal and hard coal, both of these capacities are multiplied with the same factor.

The 2030 oil capacity for the EU-27 countries was 32 GW, this is reduced to 19 GW for the 2050 scenario giving a change factor of about 0.6. Meaning that also the oil is reduced to about 60 percent of the 2030 value. Also half of the capacity formerly belonging to the mixed oil and gas generation capacity was added to the 2030 oil capacity and reduced to about 60 percent. This is done because the 2050 scenario has no data about mixed fuels so this is split between oil and gas.

The gas capacity in the 2030 scenario for the EU-27 countries was 260.74 GW. This was reduced to 182 GW in the 2050 scenario. This gave a change factor of about 0.7, meaning that the gas capacity is reduced to 70 % of the value in the 2030 scenario.

The installed nuclear power for the EU-27 countries in the 2030 scenario was 104.77 GW, this was reduced to 41 GW in 2050, giving a change factor of about 0.4, meaning that the 2050 nuclear power is only 40 percent of the 2030 nuclear power.

The last capacities to be changed was the PSST generators in the group renewable other than wind. The choice was made to assume that only the biomass plants in the 2050 scenario should be included here because this seemed most consistent with the marginal costs in the PSST model. The 2050 scenario also include some smaller amount of geothermal, tidal and hydrogen capacity which is not included here. The renewable other than wind capacity is increased from 53.1 GW for the EU-27 countries in the 2030 scenario to 163 GW in the 2050 scenario to account for the biomass in the 2050 scenario. This gives a change factor of 3.1, meaning that the renewable other than wind is about three times higher in the 2050 scenario.

3.4.2 Installed capacities in the 2050 whole scenario.

In this section all the installed capacities that were used in the 2050 whole scenario, including the change in wind power, solar power, nuclear, fossil and biomass power is shown.

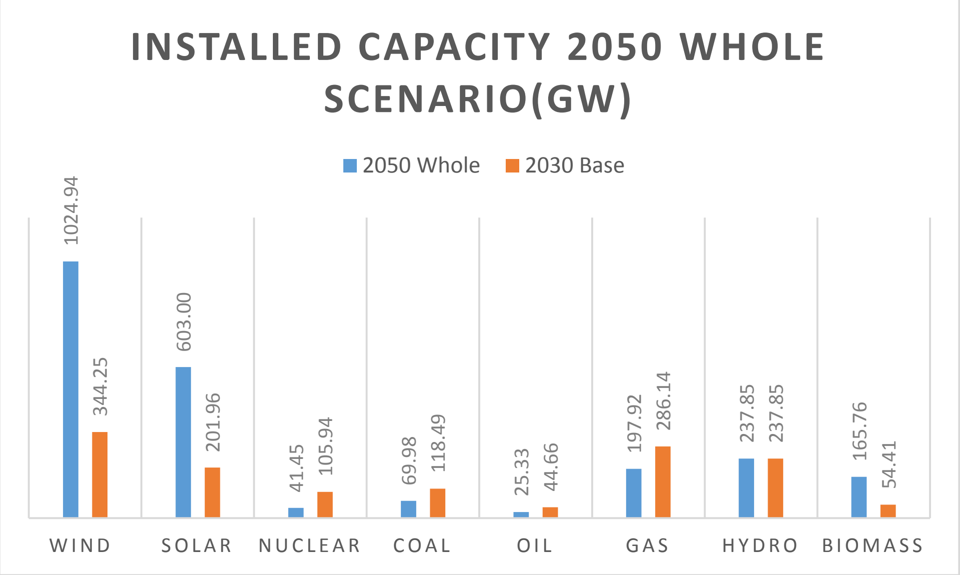


Figure 8 Installed capacities in the 2050 whole and the 2030 base scenario

The diagram shows that the 2050 whole scenario has a high increase in wind and solar capacity, a reduction in nuclear, coal, oil and gas, the hydro remains the same and the biomass is increased.

Generally there is a reduction in the fossil sources that are stable production sources and an increase in the variable sources, solar and wind.

4 Results and discussion

In this chapter the results from the simulations are presented. In chapter 4.1 the results from the 2030 base scenario are presented and analysed. In section 4.2 the results from the 2050 wind scenario are presented and analysed to see the effect on important power system parameters of increasing the wind power to 2050 level. In section 4.3 the results from the 2050 solar are analysed to see the effect on important parameters of increasing the solar power to 2050 level. In section 4.4 the results of the 2050 wind and solar scenario are analysed to find the combined effect of wind and solar on important power system parameters. At last in section 4.5 the 2050 whole scenario is presented which analyse the power system with all the parameters being as close to the 2050 high RES scenario as possible.

4.1 2030 Base Scenario

In this section some important results for the 2030 base scenario are presented and analysed. These results are used for comparison with other scenarios in the next sections. The results that are treated here are the wind power production and utilisation, the solar power production and utilisation, the fossil production, the price levels in different areas, the exchange on HVDC corridors, the congestions on AC corridors between countries and the total congestion costs.

4.1.1 Wind power production

The installed wind power capacities for the 2030 base scenario are already presented in section 3.3.1, Table 10. The countries with the definitive highest amount of wind power is Germany with 85 GW, Spain with 48 GW, Great Britain with 47 GW and France with 40 GW. The total amount of installed wind power in Europe is 344.25 GW.

The table below shows the total produced wind power in the 2030 scenario with limited and infinite grid.

2030 Base Scenario	Total Wind Prod(TWh)	Utilisation time(h)
Limited grid	791.04	2297.86
Infinite grid	801.41	2327.99

Table 12 Total wind power production and utilisation time, 2030 Base scenario

The total amount of produced wind power in 2030 is 791.04 TWh and the total amount of production with infinite grid is 801.41 TWh, meaning that the grid restrictions limit the production of wind power with 1.29 % in the 2030 base scenario. The simulations done in this work does not include any grid limitations of the AC cables inside countries apart from some limitations in the Nordic countries. This means that the grid would have caused a much higher reduction in wind power production if all possible internal grid restrictions were included. The duration curve for the wind production is shown below.

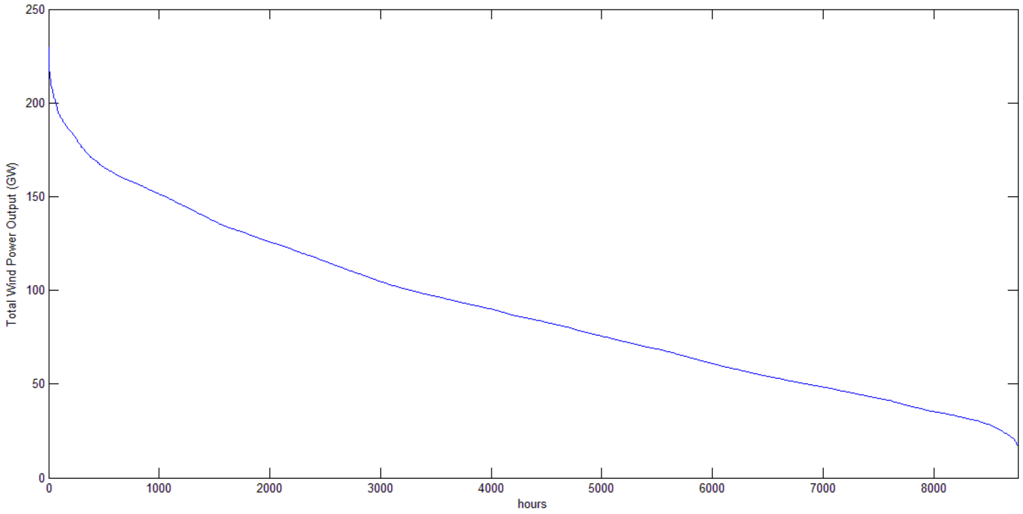


Figure 9 Duration curve, Wind power production 2030 Base scenario

The maximum production is 229.8 GW which is 66.75 % of the installed capacity. The minimum production is 17.3 GW, which is 5.02 % of the installed capacity. The mean wind production is 90.3 GW, which is 26.2 % of the installed capacity.

The figure below shows the utilisation time for the wind power plants in the 18 countries with the highest amount of installed wind power in 2030.

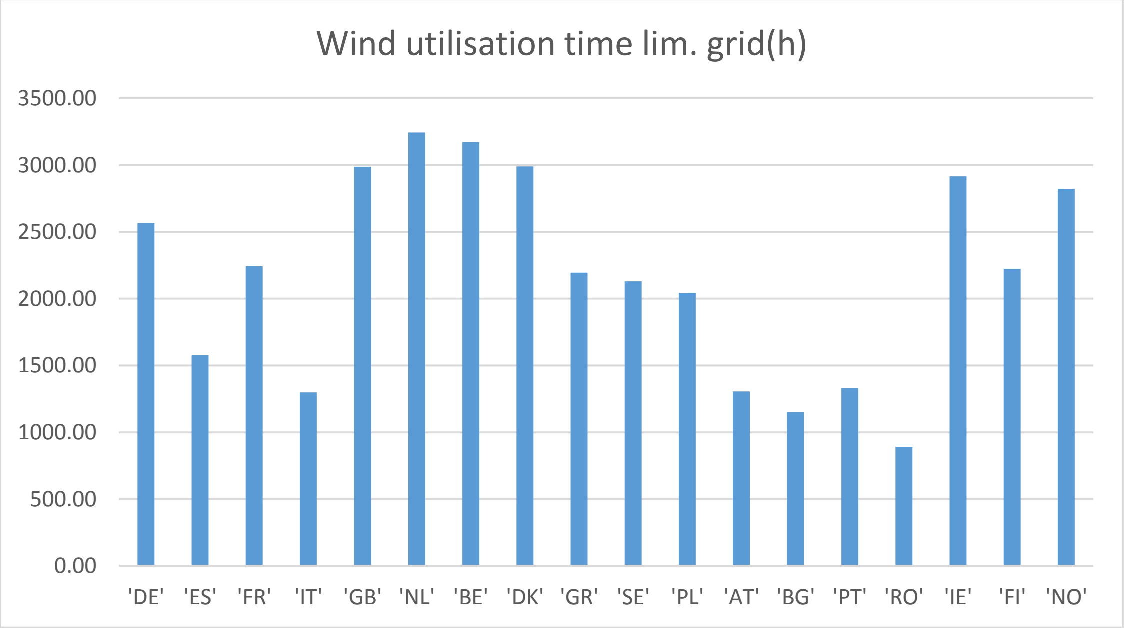


Figure 10 Wind power utilisation time 2030 Base scenario

The utilisation depends on the wind power time series at the given location and the grid that the wind farm is connected to. The demand of power and amount of installed production capacity can also be decisive for the wind power utilisation. However, the marginal cost of wind power is zero and the only way demand and supply can influence the wind power utilisation is if the supply from energy sources with zero marginal cost is higher than the demand. When the grid is limited this situation can emerge within a restricted area.

The countries that has highest share of offshore wind power compared to onshore have the highest utilisation. The countries that has the highest utilisation time, that is Great Britain, Netherlands, Belgium and Denmark all have high shares of offshore wind power. Great Britain has 76.4 % offshore wind energy, Netherlands has 50 %, Belgium 46.8 percent and Denmark has 43.4 %. The amount of offshore energy of the total installed wind is only 28.4 percent. The graph below shows an example were the potential production of an offshore wind farm is higher than an onshore wind farm. The graph shows the sorted relative potential of the Doggerbank E wind farm outside Great Britain and a wind farm far from the coast in Germany.

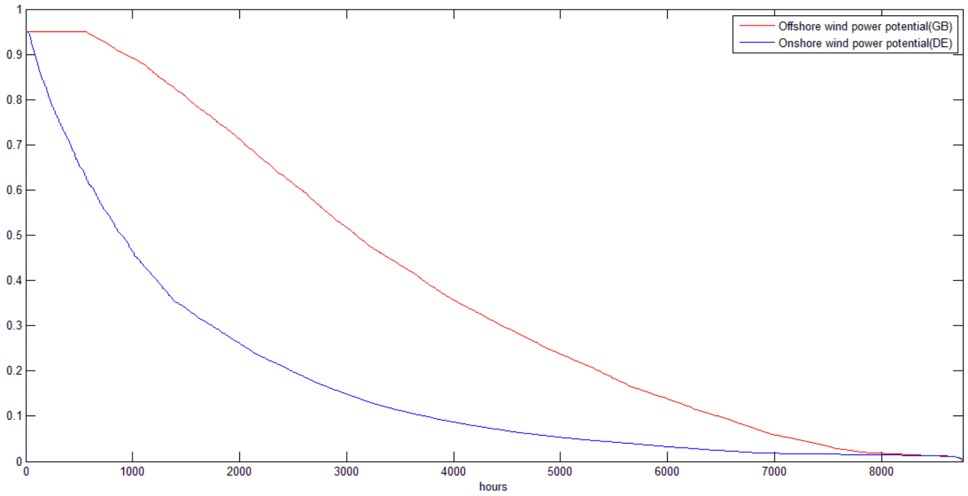


Figure 11 Sorted relative wind potential Doggerbank E and onshore wind farm in Germany

The graphs above shows that the potential is higher for the offshore wind farm for all the hours. Therefore it makes sense that the utilisation time for the countries with the highest share of offshore wind is higher than for those with more onshore wind.

It is also interesting to look at how the grid influence the duration of wind power in the different countries, therefore the difference in utilisation time with limited grid and with infinite grid is shown below.

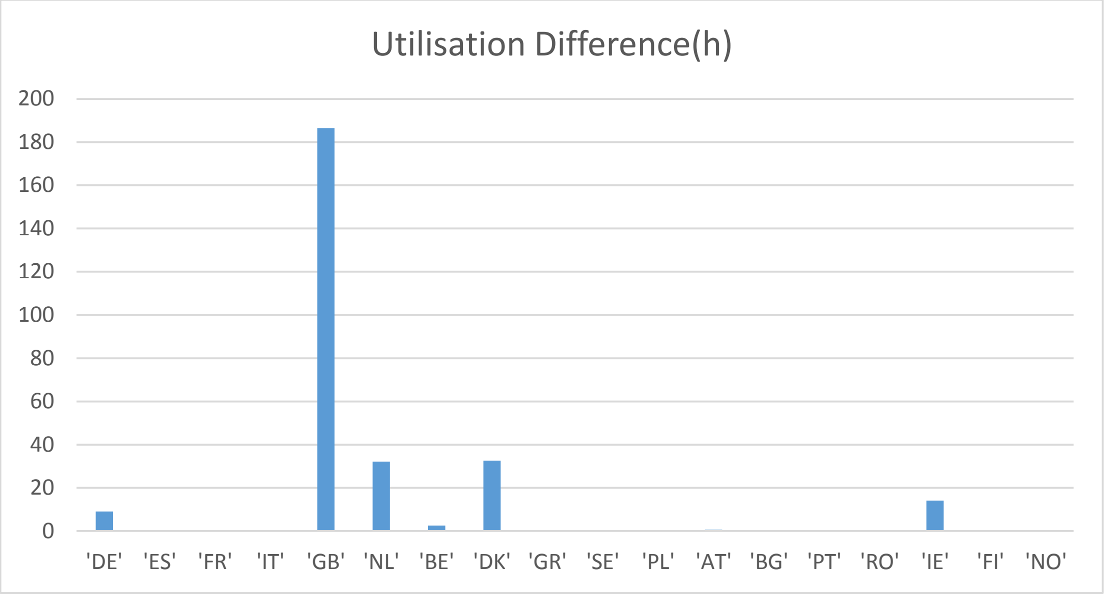


Figure 12 Wind Utilisation difference (Inf grid-Lim grid), 2030 Base scenario

The only countries where the utilisation time seems to be substantially influenced by the grid are Germany, Great Britain, Netherlands, Denmark and Ireland. Especially Great Britain where the grid restrictions reduces the utilisation time with 186 hours. Great Britain, Netherlands and Denmark are all countries with a high amount of offshore wind power compared to onshore. This might cause the grid to influence the utilisation time more because the offshore wind farms are in clusters close to each other, which gives low geographical smoothing and might put a high stress on the grid to which the wind farms are connected.

4.1.2 Solar production

In this section the solar production in the 2030 base scenario is analysed. The total amount of installed solar power in the 2030 base scenario is 201.96 GW. The highest shares of solar capacity is situated in Germany(68.8GW), Italy(42GW), France(30GW) and Spain(24.3GW). The table below shows the total solar production in the 2030 base scenario for limited and infinite grid together with the utilisation times.

2030 Base scenario	Total Solar Prod(TWh)	Utilisation time(h)
Limited grid	275.77	1365.47
Infinite grid	277.04	1371.76

Table 13 Total solar power production and utilisation time, 2030 Base scenario

The total solar production in the 2030 base scenario is 275.77 TWh with limited grid, and 277.04 TWh with infinite grid, this means a change of solar production of 1.27 TWh due to the grid limitations between countries. As with wind capacity the effect of the grid would have been higher if grid restrictions inside countries were to be included. One of the differences between wind and solar is that solar often is located close to the consumption centres, and it is not sure that the internal grid restrictions would influence the solar production as much as it would the wind production.

The solar duration curve is shown below.

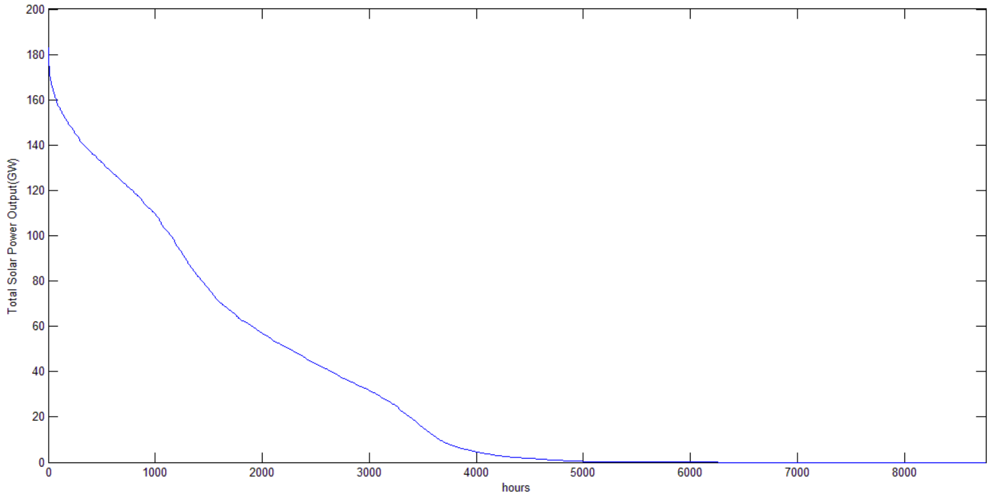


Figure 13 Duration curve, Solar power production 2030 Base scenario

The solar duration curve shows a very different characteristic compared to the wind power duration curve. The solar power maximum production is much closer to the total installed capacity, but the production is zero or close to zero for a large percentage of the year. This is caused by the annual and diurnal variation in solar radiation. The maximum output of solar production is 183 GW, which is 90.61 % of the maximum capacity, the mean solar production is 31.48 GW, which is 15.59 % of the total installed capacity. The annual variation of solar power for Germany which has 68.8 GW of solar power are shown below.

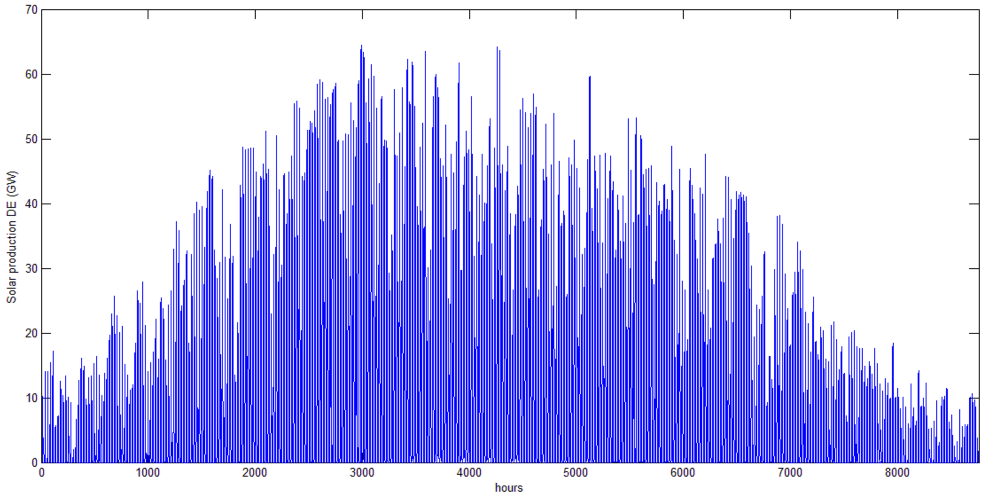


Figure 14 Solar Production in Germany, annual variation

The annual production pattern in Germany shows that the production is low during the winter and high during the spring, summer and fall. For most of the European countries, for example for Germany, the solar production peaks in the period when the load is lowest. The diurnal pattern of solar power production is shown below.

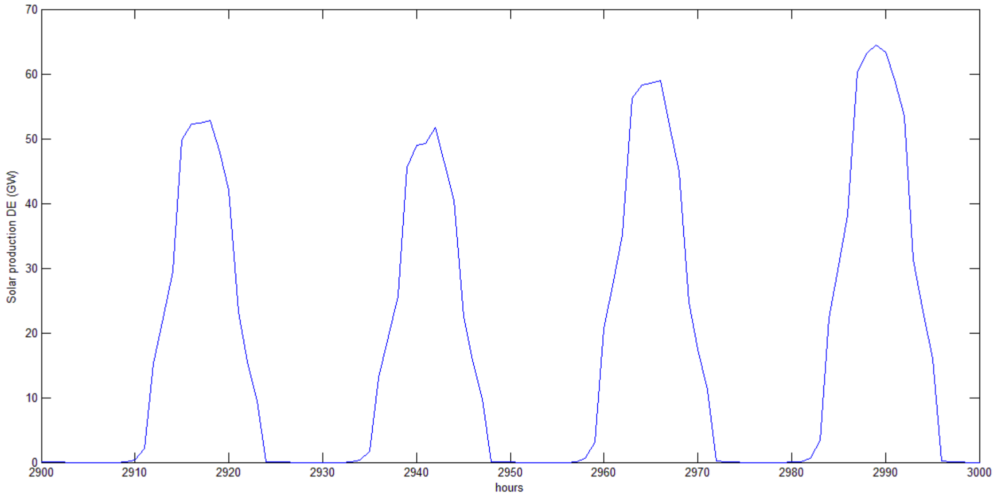


Figure 15 Solar production in Germany, diurnal variation

The figure shows that the highest production is reached in the middle of the day, while there is about twelve hours with zero production during night. This is beneficial as the load also is highest during the day.

Next the utilisation of solar power are presented, this is only presented for the countries that has 3 GW or more of installed solar power, because many of the countries have very small amounts or zero installed solar power.

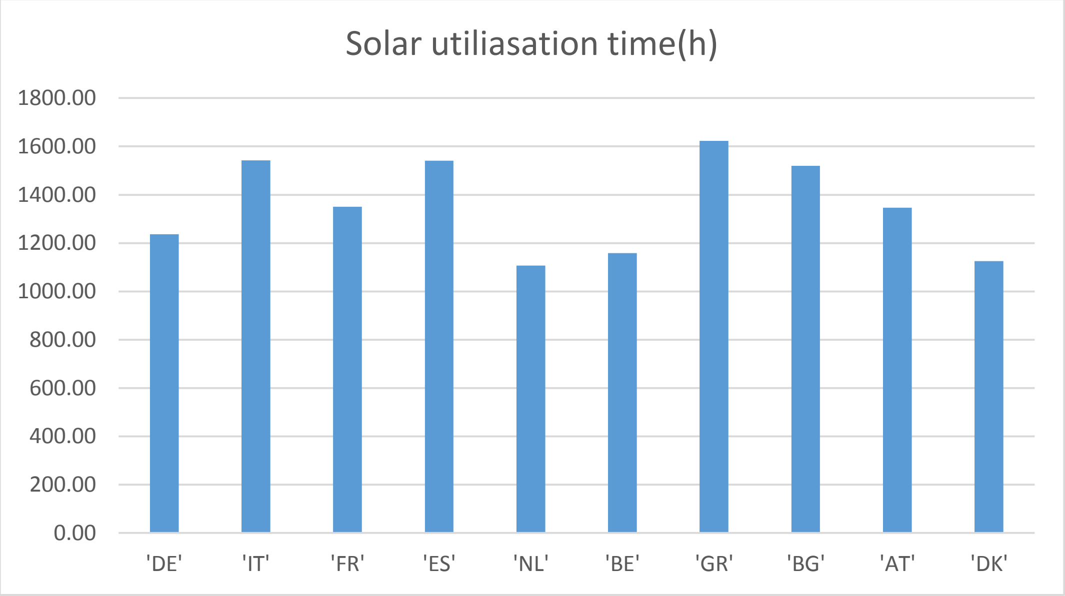


Figure 16 Solar power utilisation time 2030 Base scenario

The solar utilisation times are much lower than the utilisation times of the wind. The solar utilisation time for the different countries are more uniform than the wind utilisation times. Italy, Spain, Greece and Bulgaria has higher utilisation times than for example Germany and the Netherlands. This is because these countries are located further south and therefore gets the solar radiation at a more beneficial azimuth.

Next the effect of the grid on the utilisation of solar power is shown.

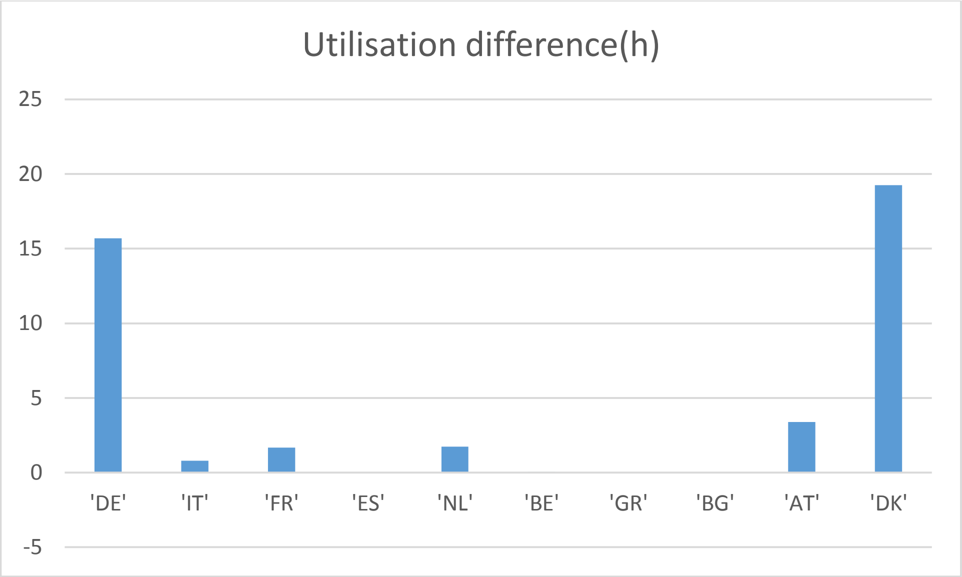


Figure 17 Solar Utilisation difference(Inf grid-Lim grid), 2030 Base scenario

The figure shows that the influence of the grid is modest for all countries. Germany and Denmark are the only countries with a noticeable reduction in utilisation time. The reason why the highest difference is for Germany and Denmark might be that these are countries with stronger seasonal differences than for example France, Italy and Greece. For Germany and Denmark the load is low during the summer when the solar production is highest which might cause the production to be high compared to the load and therefore the grid might become congested.

4.1.3 Fossil fuel production

Next the fossil fuel production for the 2030 base scenario is considered. Fossil fuel powered plants include coal, oil, gas and mixed fuels. The total amount of installed capacity in fossil fuel powered plants are 442.42 GW. The utilisation of the fossil fuel power is much higher than both wind and solar power, it is 3149.4 hours, so the total amount of production is 1393.35 TWh, which is higher than the solar and wind production combined. The load duration curve of the fossil production is shown below.

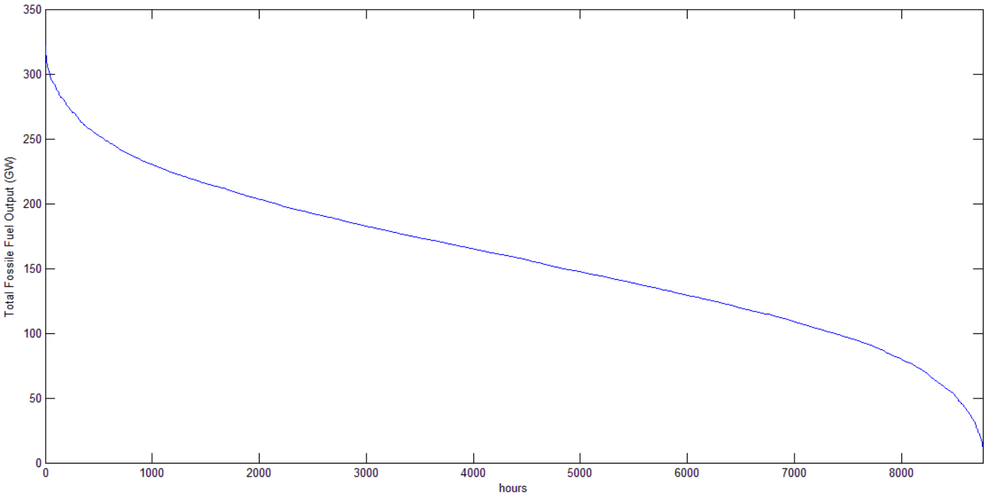


Figure 18 Fossil fuel duration curve, 2030 Base scenario

The utilisation curve shows that all the fossil fuel capacity are never utilized at the same time since the total amount of installed capacity is 442.42 GW. The maximum production is 321.5 GW, which is 72.67 % of the installed capacity. The mean production is 159.1 GW, which is 35.96 %. The fossil fuel production is different from the wind and solar production, because the fossil plants have the potential of producing at maximum capacity at all times, whereas the wind and solar potential are dependent on radiation and wind speed. The fact that all the fossil capacity is never used shows that not all the capacity are needed for production, but the fossil capacity still helps to improve the security of supply.

To look at the correlation between the wind power and thermal production in Germany the wind power is drawn in red and the thermal power in blue in the figure below

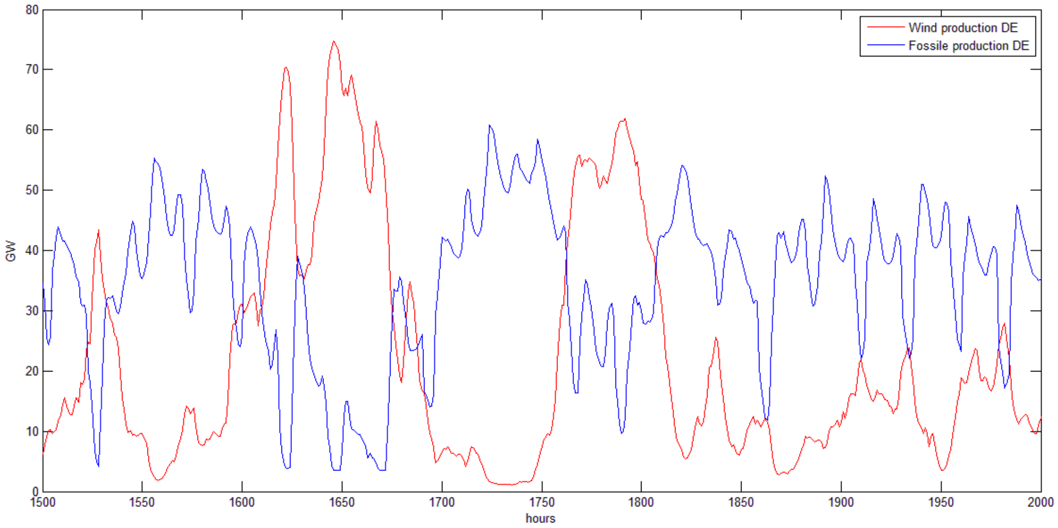


Figure 19 Wind and solar production Germany, 2030 Base scenario

The figure shows that there is a strong negative correlation between the wind power production and the thermal production. This shows that in Germany the thermal production is used to compensate for the variation in wind power. Since the marginal cost of thermal power is much higher than wind power the choice will always be to produce as much as possible from wind power and as little as possible from thermal power. The minimum wind production in Germany is 1.02 GW and happens in hour 1736, at this hour the thermal production is 54.59 GW. The installed fossil power is 78.26 GW, so even with the wind at the lowest level there is still available fossil power. The maximum amount of fossil production is 67.92 GW and happens in hour 716. In the hour with the highest fossil production the wind production is only 1.84 GW. The maximum wind production in Germany is 75.76 GW, this is quite close to the capacity, which is 85 GW, especially considering that wind is a variable energy source. The maximum wind production is reached in hour 8317, and the thermal production in this hour is 14.57 GW. The minimum amount of fossil production is 3.58 GW and this is reached in several hours, all with high wind production. Even though the fossil production is not at its absolute minimum at the same time as the wind production reaches its maximum it is clear that there is a clear negative correlation between wind production and fossil production.

4.1.4 Prices

The prices varies according to the demand and available production capacity throughout the year. The grid determines the difference in price between different areas. The mean prices for the countries in Europe with the highest amount of renewable energy in the 2030 Base scenario are shown below.

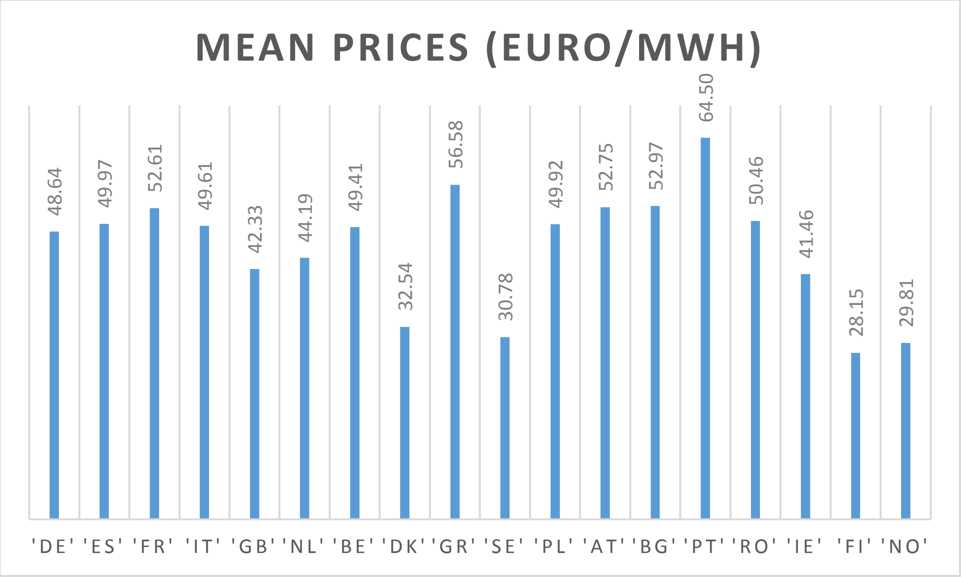


Figure 20 Mean price 2030 Base scenario

What should be noticed from the mean prices is that the Nordic countries have low prices compared to the other countries, Norway has a mean price of 29.81 Euro/MWh, Sweden has a price of 30.78 Euro/MWh and Denmark a price of 32.54 Euro/MWh. Germany and France which are the two countries with highest demand in Europe have higher prices than the Nordic countries. Germany has a price of 48.64 Euro/MWh and France has a price of 52.61 Euro/MWh. While the Nordic countries have a relative low demand and high availability of cheap renewable energy sources, the Central European countries have a high demand and a substantial amount of thermal power in addition to wind and solar power. Taking the ratio between the installed renewable capacity in Norway and the demand the ratio is higher than for Germany. In addition the renewable energy in Norway is almost exclusively storable hydro power, which can be stored and used when needed, while Germany mostly has wind and solar power which has to be used at the same time as it is produced if no extra storage is installed.

Portugal is the country with the highest price of all countries. The prices for Portugal is highest during summer and early fall. Portugal is a country with 10.26 GW installed hydro and 6.34 GW installed wind in addition to 4.6 GW of gas. The reason for the high prices in the summer and fall are the low hydro production in this period. The reservoir level is also checked for Portugal and the reservoir is at its lowest during this period. This is different from the Nordic countries which has the lowest reservoir level in the early spring. Portugal generally has a low amount of installed capacity compared to the load, which will make the prices high.

It is also worth noticing that Great Britain has a lower price than many of the continental European countries. Even though there are not a higher amount of renewable energy compared to load in Great Britain than in Germany there are several factors that might keep the prices down here. Germany has a higher installed wind power capacity than Great Britain, but the utilisation time is a lot higher in Great Britain. In addition Great Britain has 13.91 GW of installed nuclear power which will lower the price. The 1400 MW connection to Norway will also help lowering the prices.

4.1.5 Production mix in Europe in the 2030 Base scenario

In this section the overall production from each generation source as a percentage of the total production is shown. This will give an overview of how much the renewable production has taken over for the thermal production in this scenario. The share of each production source is shown in the diagram below. The oil is not shown because it has a very low percentage of the total production and cannot be seen in the diagram.

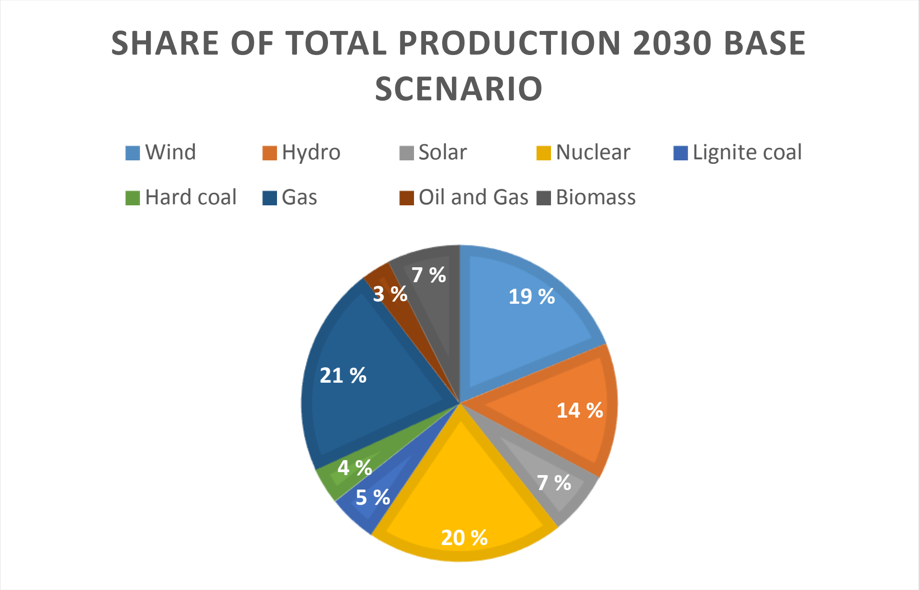


Figure 21 Share of the total production from each generation type

The figure shows that the highest amount of production in the 2030 base scenario comes from gas fired power plants. After this comes nuclear power plants, closely followed by wind power plants. Of the renewable power production the highest share comes from wind and hydro, the solar power only constitutes 7% of the total production in the 2030 base scenario.

To get an overview of how much of the production that is renewable(Wind, solar, hydro and biomass) and how much is non-renewable, the share of each is shown in the diagram below.

The share of renewable power

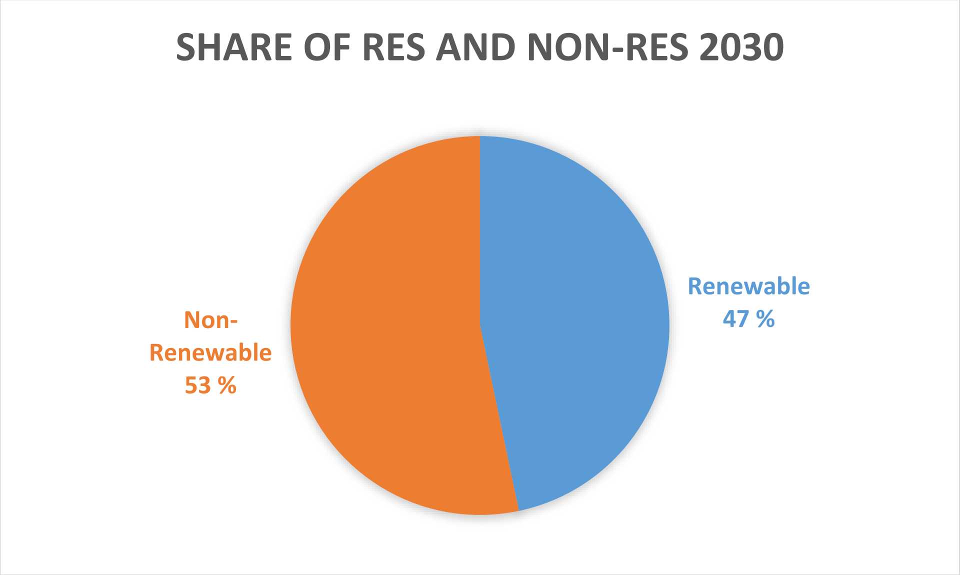


Figure 22 Share of RES and Non-RES production of total production

In the 2030 Base scenario the highest share of production still comes from non-RES plants, but a significant share of the production also comes from RES, amounting to 47% for wind, hydro, biomass and solar combined.

4.1.6 Exchange

In the map shown in Figure 2 in chapter 2.3.1 all the HVDC cables in Europe are shown together with the wind farms.

The map shows that between some of the countries such as Norway and Great Britain and Norway and the Netherlands there is only one HVDC cable connecting the two countries. Between some countries there are several cables connecting them, for example there are three cables connecting Great Britain and France.

The table below shows the utilisation of some of the HVDC corridors. The table shows the total utilisation of the corridor and the utilisation of the corridor in each direction. Adding up the utilisation in each direction will give the total utilisation. The first seven rows in the table are the overall transmission between the countries, because these countries are only connected by HVDC lines. The three rows at the bottom are the utilisation of individual cables, because these countries are also connected with AC lines.

Transmission Line		Capacity	Utilisation(%)		
From	To		Total	From-To	To-From
NO	GB	1400	98.86	91.51	7.35
NL	NO	1400	99.37	0.51	98.85
DE	NO	1200	99.01	7.22	91.79
NO	DK	1700	73.32	26.92	46.39
NL	GB	1290	90.20	33.07	57.13
BE	GB	4000	67.62	3.85	63.77
FR	GB	5000	87.91	12.37	75.53
SE	PL	792	75.33	61.62	13.70
SE	LV	1000	97.05	94.81	2.25
FI	EE	2000	94.89	93.93	0.96
FR	IE	1000	92.23	14.59	77.63
GB	IE	763	76.86	11.20	65.67
DE	SE	1486	82.19	4.01	78.18
West DK	NL	700	95.96	94.60	1.36
East DK	DE	550	87.20	74.03	13.18
East NO	SE	1100	85.88	21.18	64.70
SE	DK	485	91.49	56.06	35.43
SE	FI	2350	45.13	42.36	2.77

Table 14 HVDC utilisation 2030 Base scenario

To get a better overview of the flow of the HVDC connections between the countries, these are drawn in the map shown in Figure 23. In the cases where there are several lines between two countries only one equivalent line is drawn. It is not shown when a wind farm is placed in the middle of the cable, because the goal of this map is to visualize the main flows between countries. The numbers in black shows the total utilisation of the corridor. The closeness of the red arrow to the node in the given area tells how much of the utilisation that is in the direction of the arrow. The closer the arrow is to the node, the higher percentage of the utilisation is in the direction of the arrow.

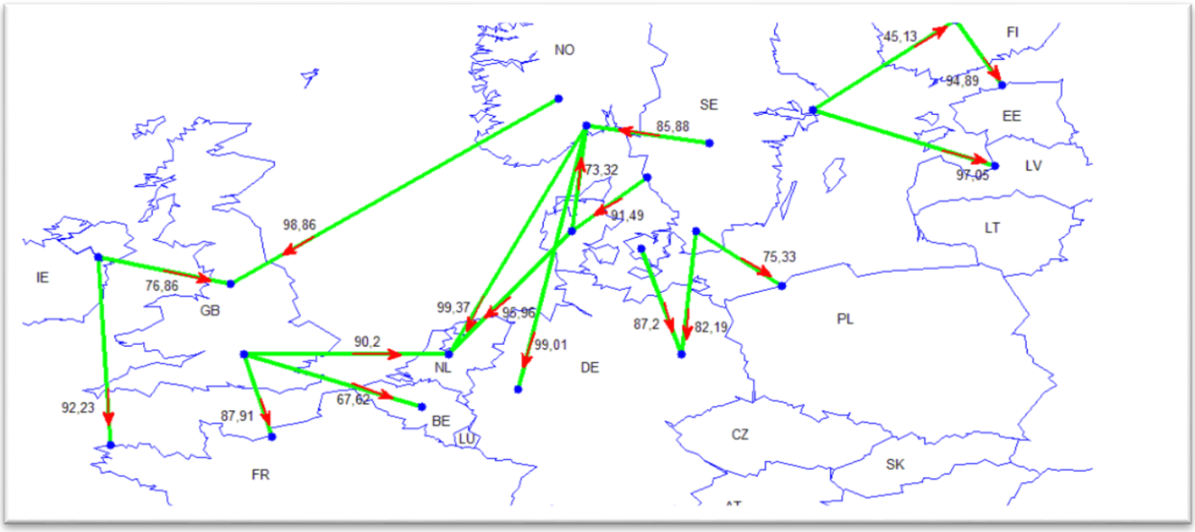


Figure 23 Map HVDC flows, 2030 Base scenario

The main conclusion that can be drawn from this map is that the Nordic countries exports power to the central European countries, that is Netherlands and Germany. Norway also exports power to Great Britain, which again exports power to France, Belgium and the Netherlands. There is also export from Sweden and Finland to the Eastern European countries, that is Estonia, Latvia and Poland.

Looking closer at the exchange between Norway and Great Britain it is seen that the utilisation of this cable is very high, with a total utilisation of 98.86 percent. The utilisation of the cable from Norway to Great Britain is 91.51 percent and the utilisation from Great Britain to Norway is 7.35 percent. The total export from Norway to Great Britain is 11222.32 GWh, while the total import to Norway from Great Britain is 901.73 GWh. This cable is planned to be finished in 2020 and is planned to be built in cooperation between Statnett and National Grid which is the TSOs in Norway and Great Britain [14]. When the wind production in Great Britain is high Norway can import power and store more energy in the hydro reservoirs. When the wind is low, Great Britain can import hydro power from Norway. Most of the exchange on this cable is from Norway to Great Britain, so that the Norwegian hydro power contributes to balancing the variation in wind power in Great Britain. However there is also some exchange from Great Britain to Norway, this exchange takes place when the wind power production is high in Great Britain. The export from Great Britain to Norway does not seem to be influenced by the reservoir level in Norway. The high utilisation indicates that connecting the Norwegian and British market through such a cable is highly beneficial. Since most of the exchange is from Norway this cable will most likely lead to an increase in prices in Norway and a decrease in prices in Great Britain. However this is not studied further here due to the scope of the work.

The 1200 MW cable between Norway and Germany is almost a hundred percent utilized, with a total utilisation of 99.01 percent. The utilisation of the cable in the direction from Norway to Germany is 91.79 percent, while the utilisation from Germany to Norway is 7.22 percent. The total export from Germany to Norway is 758.97 GWh, while the total export from Norway to Germany is 9648.6 GWh. This shows that most of the exchange in the 2030 base scenario is from Norway to Germany, so that Germany and the countries connected to Germany can benefit from the flexibility of the Nordic hydro power. Germany has a lot of variable wind and solar power and in periods with high wind and solar

Norway can benefit from this by importing cheap fluctuating power instead of using storable hydro power.

The 1400 MW cable between the Netherlands and Norway has the highest utilisation of all the HVDC cables studied here. The total utilisation is 99.37 percent. The utilisation from Norway to the Netherlands is 98.85 percent, while the utilisation from Netherlands to Norway is only 0.51 percent. The total export from Norway to the Netherlands is 12123.57 GWh, while the total export from the Netherlands to Norway is only 62.95 GWh. This means that there is even higher export from Norway to Netherlands than there is from Norway to Germany. The Netherlands has a much lower amount of variable renewable power than Germany and Germany might therefore experience more extreme production peaks, which lead to lower prices than the Netherlands. Also the amount of installed fossil fuel powered plants in relation to the amount of wind and solar power is much higher in Netherlands than in Germany. In Germany the total amount of installed wind and solar is 153.80 GW, while the total amount of installed fossil power is 78.26 GW, meaning that the ratio between variable renewable capacity and fossil capacity in Germany is 1.95, in Netherlands the amount of installed wind and solar power is 20 GW, while the amount of installed fossil fuel power is 26.21 GW, giving a ratio of 0.76. The reason for the higher amount of export from Germany to Norway than from Netherlands to Norway might therefore be that Germany experience higher production peaks and will have lower prices than Norway in more occasions than the Netherlands will. The Netherlands can balance more of its production variation with own fossil plants, whenever this is more beneficial than importing from Norway. Germany that has a low amount of fossil plants compared to variable renewable energy do not have the same opportunity.

Norway imports more from Denmark and Sweden through the HVDC cables than it exports, even though Norway as a whole has lower mean price than both Denmark and Sweden. However there are some grid limitations inside Norway and these causes the price to be different in the zones within the country. Eastern Norway that is connected to the HVDC cables to Sweden and Denmark has higher mean price than Norway as a total. Eastern Norway also has a higher mean price than many of the Swedish zones. Denmark is divided into two zones, eastern Denmark and Western Denmark. East Denmark has an average price of 46.8 Euro/MWh, while western Denmark has an average price of 28.35 Euro/MWh. The average price in eastern Norway is 30.68 Euro/MWh. The HVDC cable between Norway and Denmark is connected to western Denmark where the average price is lower than in eastern Norway. It is therefore natural that the main flow goes from Denmark to Norway. The prices in the two zones of Denmark are very different from each other and this is because the only connection between them is a 600 MW HVDC cable. This cable is very congested. The reason for the congestion is that the overall production in Eastern Denmark is 19.9 TWh, while the total load is 32.8 TWh. In Western Denmark the total production is 30.2 TWh, while the load is 8.7 TWh. This will give high supply compared to load in western Denmark and low supply compared to load in Eastern Denmark.

Great Britain is connected with HVDC cables to France, Belgium and the Netherlands. The cable between Great Britain and Belgium is part of the split offshore grid design, which was described in chapter 2.3.1, and has a wind farm with a capacity of 4000 MW connected to it. The wind farm belongs to Belgium and contributes to increasing the flow from Belgium to Great Britain. The highest utilisation is on the cable between Great Britain and the Netherlands. However this is also the connection with the lowest transmission capacity. The flow goes in both directions, but with the highest share from Great Britain to the Netherlands. For the two other connections a much higher share is export from Great Britain. This is linked to the fact that Great Britain and Netherlands are closest to each other in price. Both of these countries benefits from a strong connection to Norway. The utilisation of the HVDC connection between Great Britain and Belgium is quite low. It is especially low in the split connection indicating that the transmission capacity on this connection might be too high. Even though the price in Great Britain is about 10 Euro/MWh lower than in France there is still some export from France to Great Britain. This is probably caused by the high amount of renewable energy sources in both these countries and that the RES production might be out of phase with each other. The fact that France has 30 GW of solar power and that Britain has none will contribute to the RES production being out of phase.

4.1.7 Congestions in AC corridors

The map below indicates the most congested AC transmission corridors in the 2030 base scenario. The eleven most congested lines are shown, the arrow shows the direction of the congestion and the number written in black shows the total number of hours with congestions across the given border. If the arrow is pointing in both directions it means that the hours of congestion are approximately equal in each direction. For the congestion to be bidirectional no more than 60 percent of the congested hours can be in a specific direction.

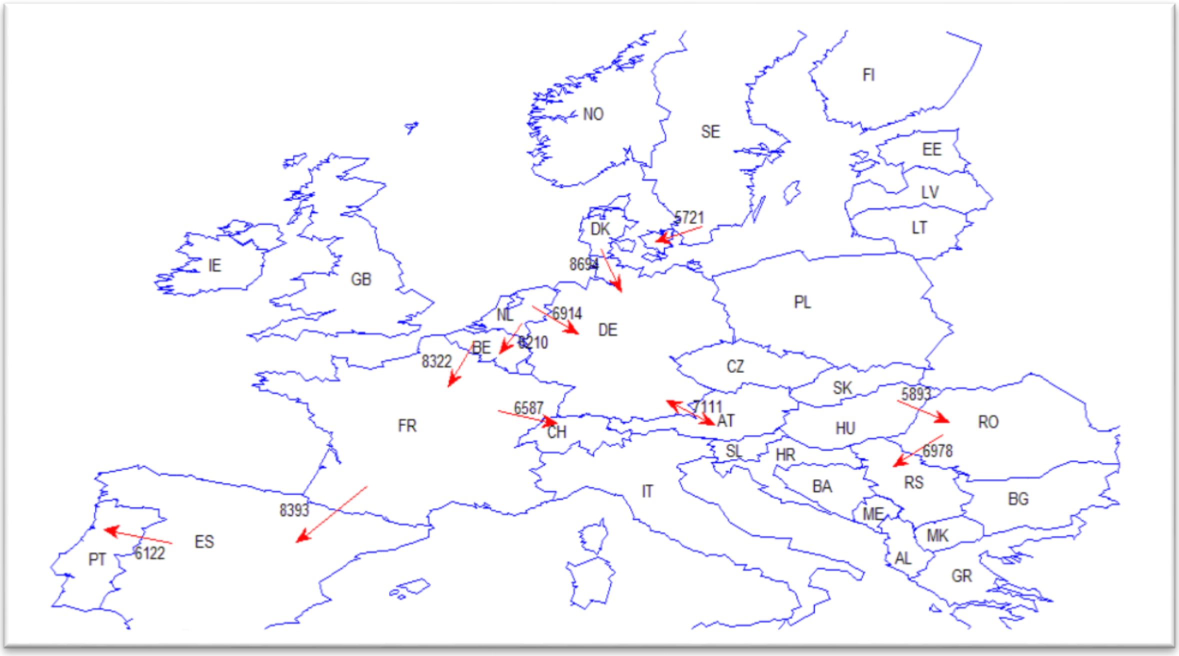


Figure 24, The most congested AC-corridors, 2030

The congestions seen illustrates that the power is transported from Northern Europe to central and southern Europe. The Netherlands for example receives a lot of power from Great Britain and Norway and transports this further to Belgium and Germany. The border with the most hours of congestions are the border between Western Denmark and Germany, with a total of 8694 hours of congestions during a year. This is because the prices in Western Denmark are a lot lower than the prices in Germany. It is natural that the line between Denmark and Sweden is congested, since Sweden shares a border with Eastern Denmark. As mentioned in the previous section the price in Eastern Denmark is much higher than the price in western Denmark and also much higher than the prices in Sweden. There are also a lot of congestions over the border between France and Spain. These are in the direction from France to Spain in spite of the fact that the mean price are higher in France than in Spain. Still there is only 62 percent of the hours with congestions that are from France to Spain. There are also a lot of hours with congestions over the border from Spain to Portugal. This is because Portugal has a very high price due to a general deficit in production capacity.

4.1.8 Congestion costs

The congestion costs are first found with wind and then without wind. This is to investigate how wind power influence the total costs in the system. When the total cost with limited grid are subtracted from the total cost with unlimited grid the congestion costs are found. Wind power is a variable energy source, and it is interesting to see how the variability of wind influence the total costs and the bottleneck costs. To investigate this simulations are done with the wind potential at each wind node equal to a constant value that is equal to the average wind potential at that node. Then the total costs are found.

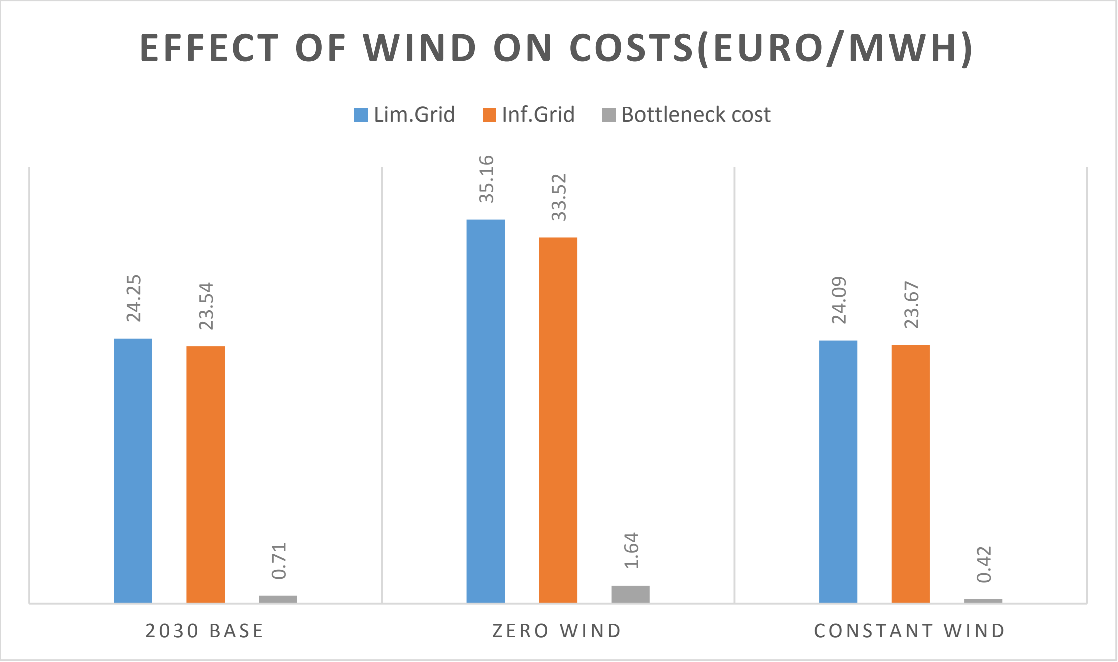


Figure 25, Total costs and bottleneck costs, 2030 base scenario, zero wind and constant wind

Figure 25 shows that the congestion costs with 2030 wind power is 0.71 Euro/MWh, while it is 1.64 Euro/MWh without any wind. This means that for the 2030 base scenario, the installed wind power capacity reduces the bottleneck costs with 0.93 Euro/MWh.

The total costs is 10.91 Euro/MWh higher with zero wind than with 2030 base scenario wind. If the wind were to be removed the wind production would be substituted with thermal production which has a much higher marginal cost, which is the main cause of the cost increase. The cost increase if there were no wind with infinite grid is 9.98 Euro/MWh, meaning that the wind would reduce the costs less if the grid was infinite. This is natural since it would be easier to distribute the available production capacity.

The limitations of the grid will cost more without wind than with wind, meaning that the wind power contributes to reducing the congestion costs. The reason for this is probably that the wind reduces the need for import in many countries, for example Germany that is a net importing country even with wind power would have to import a lot more if the installed wind power were zero. This would put more strain on the surrounding grid. To be exact Germany would import 100.9 TWh with 2030 base scenario wind and 122 TWh with zero wind. If the wind production were higher the wind might contribute to increasing the bottleneck costs, because the wind production would lead to a higher need to export for some countries, which could give a higher strain on the grid.

The total costs with constant wind and limited grid is 0.16 Euro/MWh lower than with 2030 base wind. This shows that it is beneficial when it comes to costs to have constant wind production. This might be because the lowest production levels is avoided with constant wind production. When there is very low wind production in a certain area it might be necessary to compensate with using the most expensive thermal plants which might not be needed if the wind production was at its average level. The decrease in cost with constant wind also gives an indication that it might be beneficial to use storage to compensate for the large variations in wind power production. The bottleneck cost is reduced with 0.29 Euro/MWh with constant wind compared to variable wind. This means that the variability of wind increases the grid costs. This is not surprising since the variable wind could give very high production peaks for some hours in certain areas, increasing the export from this area. If the wind production is very low in a certain area this could lead to a high need to import. This would cause a higher strain on the grid.

Figure 25 shows that with infinite grid the total costs are slightly higher with constant wind than it is with 2030 base and variable wind. This means that with infinite grid it is beneficial to have variable wind power as opposed to constant wind power. This might be due to geographical smoothing, which means that the system benefits from the fact that some wind power facilities produces at max while others do not produce at all. The effect of geographical smoothing will influence the most when the transmission capacities are infinite. Another explanation could be that the wind production follows the seasonal variations in load, this will give a better utilisation of the hydro reservoirs. The simulations do not take the start and stop costs of thermal plants into account, this will influence the comparison of the simulations.

The figure below shows the effect the solar power has on the bottleneck costs.

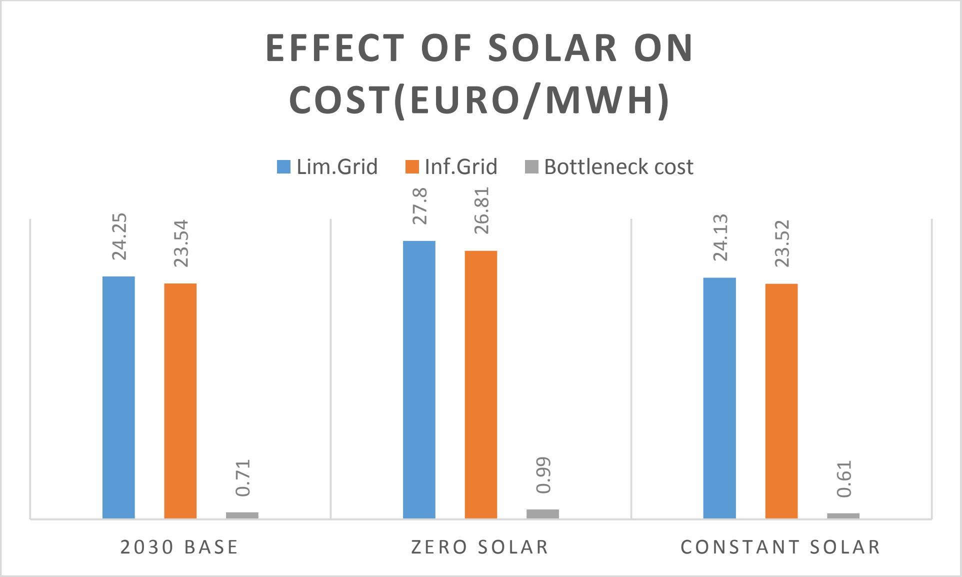


Figure 26, Total costs and bottleneck costs, 2030 base scenario, zero solar and constant solar

The diagram shows that the solar power reduces the bottleneck costs with 0.28 Euro/MWh. The total costs become higher with zero solar than with 2030 base solar for both limited and infinite grid. With limited grid the total costs are 3.55 Euro/MWh higher with zero solar than with the 2030 base solar. For comparison the wind power decreased the costs with 10.91 Euro/MWh. The reason why the cost reduction is smaller than with wind power is that there is a smaller amount of installed solar than installed wind, and the utilisation time of solar power is a lot lower. With infinite grid the total costs are 3.27 Euro/MWh higher with zero solar than with 2030 solar, meaning that the solar power reduces the costs a bit less with infinite grid than with limited grid. This is probably caused by the fact that it is easier to distribute the available production capacity. In the same way as with wind power the total bottleneck costs are reduced with 2030 base solar compared to no solar, showing that the solar power also is beneficial for the grid costs. The explanation for this is probably that some of the countries get more self-supplied with energy.

The total costs are lower both with limited and infinite grid when the solar is constant compared to when it is variable. Making the solar constant is also beneficial for the grid costs, since the bottleneck costs are reduced by 0.1 Euro/MWh. The diurnal pattern of solar radiation is beneficial because the sun shines during the day when the load is high, and it does not shine during the night when the load is low. The seasonal variation might not be that beneficial, especially in countries with cold winters, since there is more solar radiation during the summer than during the winter when the need for heating is at its highest. Therefore it could be beneficial to make the solar constant so that more power can be produced during the winter. In this way fewer expensive thermal plants, such as oil and coal plants need to be started during the winter and the costs become lower. In addition constant solar power will improve the utilisation of the hydro reservoir capacity. This is because the reservoir level is already at a high level during the summer when the solar production is at its peak and the available energy storage capacity is therefore limited.

Next the consequences for the 2030 system of setting both the wind and the solar equal to zero or a constant value are investigated. The congestion costs of the system if there was no solar and no wind, or if both the wind and the solar were constant are shown in the table below.

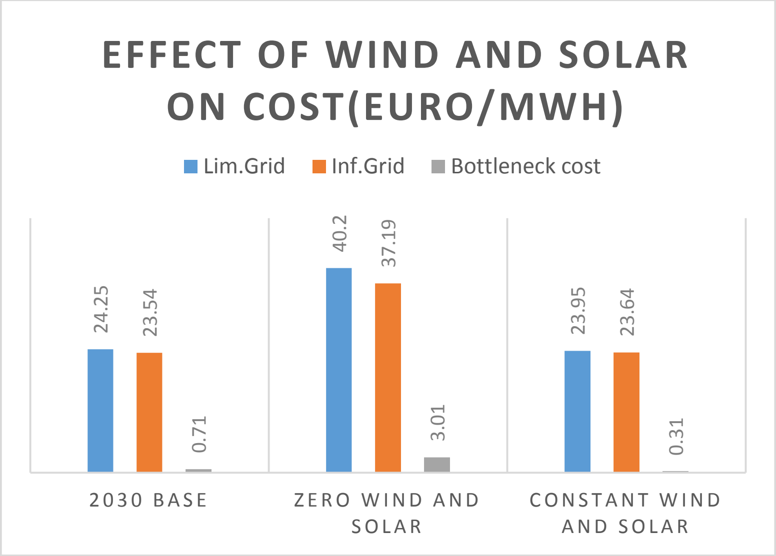


Figure 27, Total costs and bottleneck costs, 2030 base, zero wind and solar and constant wind and solar

The figure shows that the wind and solar combined contributes to a high decrease in total costs. Without wind and solar the total cost is 40.2 Euro/MWh, with wind and solar the cost is 24.25 Euro/MWh. This means that the wind and solar combined decrease the total costs with 15.95 Euro/MWh. Earlier in this chapter the decrease in costs caused by the wind and solar separately was found, the sum of these were 14.46 Euro/MWh. This shows that the combination of wind and solar is beneficial when it comes to reducing the total costs. The reason for this is that wind production follows the seasonal variation of the load while the solar power follows the diurnal variation of the load. This leads to a beneficial combined production pattern that follows the load pattern better than the wind and solar production do separately.

The wind and solar combined leads to a decrease in bottleneck costs of 2.3 Euro/MWh. This shows that the high import that would be needed in some countries would put a higher strain on the grid.

The bottleneck costs are reduced with 0.4 Euro/MWh if both the solar and the wind production was constant and equal to its average production. Looking at the total costs with constant wind and solar and limited grid the diagram shows that the costs have decreased with 0.3 Euro/MWh compared to the 2030 base scenario. The total costs with constant wind and solar and infinite grid on the other hand has increased with 0.1 Euro/MWh compared to the 2030 base scenario. This also happened when only the wind was made constant. With constant wind the increase in total costs with infinite grid was 0.13 Euro/MWh. Since the costs for the infinite grid with constant solar decreased it seems likely that it is the constant wind that causes the increase in costs when the grid is infinite. This shows that when the grid is infinite it is beneficial that the wind varies compared to being constant equal to its average potential. This is most likely due to the beneficial seasonal production pattern of wind power.

The table below sums up all the congestion costs for the 2030 base scenario.

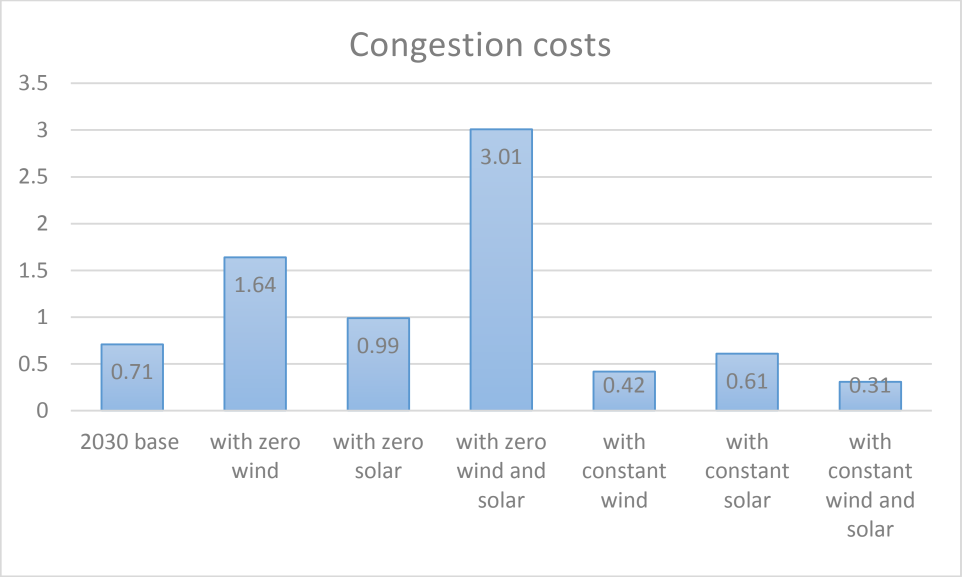


Figure 28, Total congestion costs in Euro/MWh

The table shows that setting either wind, solar or both to zero increases the congestion costs, while setting the wind and solar potential constant decreases the congestion costs.

4.1.9 Load shedding in the 2030 base simulations

When the system is not able to supply the load, this is solved by using load shedding. Load shedding has a cost that is equal to the rationing price which in these simulations are set to 375 Euro/MWh. In this section it is stated in which of the above simulations there is load shedding, how much this is and if it is high enough to influence the costs substantially.

There is no load shedding in any of the simulations when the grid is infinite. Even with zero wind and solar all the load can be supplied with infinite grid.

There is some load shedding in the 2030 base scenario, but this is only 46.5 GWh, which is 0.001 percent of the total load. All the load shedding in the 2030 base scenario is in Eastern Denmark, again showing that this is a constrained area.

Without any wind the total load shedding has increased to 3774.2 GWh, which is 0.0898 percent of the total load. This time it is not only Denmark that experience some load shedding, but several of the other countries as well.

Without any solar the total load shedding is 96.32 GWh, which is 0.002 percent of the total load. In this case it is Denmark and France that has load shedding. It is expected that the load shedding with zero solar should be higher than the 2030 base and lower than with zero wind.

With zero wind and solar the total load shedding is 9918.5 GWh which is 0.24 percent of the total load.

The load shedding in all scenarios are considered to be so low that it does not affect the costs substantially.

However the fact that there is increased load shedding both with zero wind and with zero solar shows that the system is dependent on these energy sources to supply the load at least as long as there is grid restrictions. It is likely that there would have been more load shedding if the grid limitations inside each country were included.

4.1.10 Effect of Congestions on prices

It is interesting to look at how the limitations in the grid influence the prices in the different areas. The prices with grid limitations were shown in the table under the section about prices. The prices with infinite grid is the same in all areas and equal to 48.33 Euro/MWh. The diagram below shows the difference in price with limited and infinite grid for the 18 countries with the highest amount of renewable energy installed. It shows positive numbers for those countries that experience a price increase when the grid is set to infinite and negative numbers for those countries who experience a price fall.

Figure 29, Price(Inf grid)-Price(Lim.grid), 2030 Base scenario

In the countries with high prices with a limited grid, the prices decrease. For example, there is a price reduction of 4.28 Euro/MWh in France. Looking at France in Figure 24 showing AC congestions it can be seen that there is a lot of congestions between France and the surrounding countries. All the Nordic countries experience a high increase in prices while the continental countries experience a decrease. From the table you get the impression that there is little decrease in prices considering the high increase of prices in the Nordic countries. This is natural since it is the most expensive unit that at all times set the price.

In addition to the Nordic countries Great Britain, Netherlands and Ireland experience a substantial price increase, even though it is not as high as in the Nordic countries. This is consistent with the diagram showing the mean prices where it was seen that these countries have the lowest prices after the Nordic countries. Great Britain and Ireland has a high amount of wind power which helps to reduce the prices, in addition there is a strong HVDC cable between Great Britain and Norway which also contributes to reducing the prices. Netherlands has a high amount of wind power in addition to strong connections with both Norway and Western Denmark which both have very low prices.

4.2 Simulations with wind and solar capacity set to 2050 level

Three sets of simulations are performed to investigate how the grid and the energy system react on increasing the amount of variable renewable production to 2050 level. First the wind production is increased to 2050 level while the solar production is kept at 2030 level, then the solar production is increased to 2050 level while the wind production is kept at 2030 level. Then the wind and solar production are both increased to 2050 level.

4.2.1 Wind Power Production

In two of the scenarios the wind power is increased to 2050 level, that is in the 2050 wind scenario and the 2050 wind and solar scenario. In these scenarios the installed wind power capacity is increased from a total amount of 344.25 GW in 2030 to a total amount of 1024.9 GW in 2050. This means that the wind capacity is almost tripled compared to the 2030 base scenario.

The total amount of produced wind power for all of Europe was 791.04 TWh in the 2030 base scenario, for the 2050 wind scenario this had increased to 1875.5 TWh. The installed wind capacity is tripled compared to 2030 level, while the produced wind power is increased with about 2.4 times. This shows that not all the new capacity can be utilized for production.

Next the wind duration curve for the 2050 wind scenario is shown together with the wind duration curve for the 2030 base scenario.

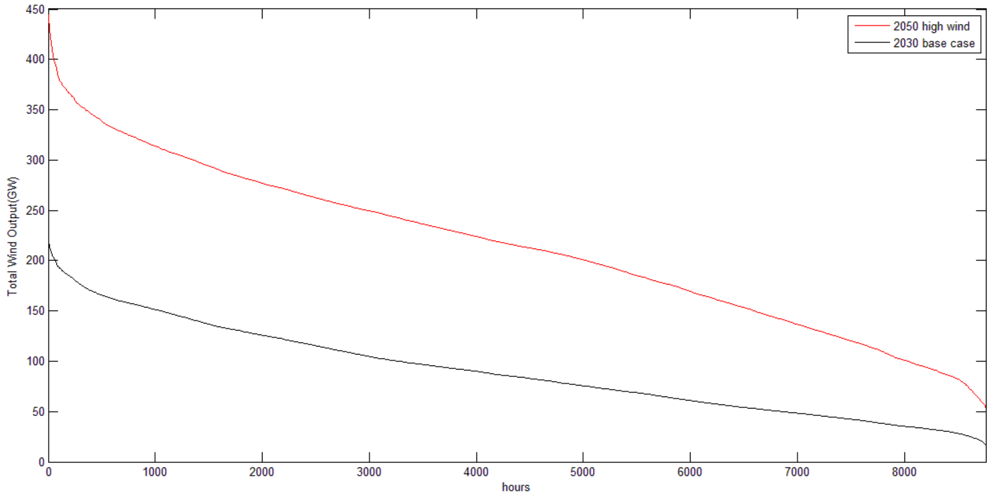


Figure 30, Duration curve, 2050 wind and 2030 base scenario

The duration curve shows that the 2050 wind scenario has a much steeper fall at the highest capacities, indicating that it can produce at the highest capacities for a very limited amount of hours.

The maximum wind power output of the 2050 wind scenario is 444.3 GW which is 43.35 % of the installed capacity. For comparison the maximum output for the 2030 base scenario was 66.75%. This means that a lower percentage of the capacity can be used with the 2050 installed capacity. The minimum production was 53.09 GW, or 5.18 % of the installed capacity. The minimum production in the 2030 base scenario was 5.02 % of the installed capacity. This is almost the same percentage. The mean production for the 2050 wind scenario was 214.1 GW, which is 20.89 % of the installed capacity. In the 2030 base scenario the mean production was 26.2% of the installed capacity. The maximum output decreases with 23 percentage points, while the mean output is decreased with only 6 percentage points compared to the 2030 base scenario. One reason why the maximum capacity has decreased is that for some areas the wind production with this high amount of wind power might exceed the load, and due to grid limitations the excess power cannot be transferred to other areas. Another reason might be that the correlation factors between the wind production at different locations has changed, because the onshore and offshore wind farm capacities are scaled with different factors.

The table below shows the total wind production and the overall utilisation time for all the scenarios.

Scenario	Installed Wind Cap(GW)	Total Wind Prod(TWh)	Utilisation time Lim.grid(h)	Utilisation time Inf. Grid(h)
2030 Base	344.25	791	2297.75	2327.99
2050 Solar	344.25	786.4	2284.39	2327.99
2050 Wind	1024.9	1875.5	1829.93	2382.48
2050 Wind and Solar	1024.9	1860.6	1815.40	2380.62

Table 15 Wind Power Production and wind utilisation, all scenarios

The table shows that the utilisation times are much lower for the two scenarios with increased wind power capacity than for the other two scenarios. This is because all the wind power cannot be utilized in all areas due to the grid limitations as mentioned earlier.

It is worth noticing that with limited grid the utilisation time is higher for the 2030 base scenario than the 2050 solar scenario. This is because the solar production sometimes creates congestions in the grid. With infinite grid the utilisation time for the 2030 base scenario and the 2050 solar scenario are the same.

The table shows that with infinite grid the utilisation of wind power is higher for the two scenarios with 2050 wind capacity than for those with 2030 wind capacity. When looking closer at the difference in utilisation between the countries for 2030 infinite grid and 2050 infinite grid it is found that the increase in utilisation with 2050 wind is partially caused by a high increase of utilisation in Norway when the grid is infinite. This is because there are three new wind farms added in Norway in the 2050 wind scenarios compared to the 2030 wind scenarios. These are three large offshore wind farms in the North Sea, and it is natural that these increase the utilisation of wind. The offshore wind power is increased with a higher factor than the onshore wind power for all countries which will also contribute to an increase in utilisation for the two scenarios where the wind power is increased to 2050 level. This effect is not the same when the grid is limited because there are limitations on how much wind power that can be transferred between the internal zones in Norway and on the HVDC cables.

The wind utilisation with 2050 wind and solar is lower than the utilisation with just 2050 wind. For the infinite grid simulations the utilisation time for the 2050 wind scenario is still a bit higher than for the 2050 wind and solar scenario showing that in this case it is not only the grid limitations that lower the utilisation time. Since the installed wind capacity is the same this must be because the total potential from wind, solar and non storable hydro is higher than the load in certain periods of the year and the wind cannot be utilized for some hours.

Next the utilisation time for the 2030 base scenario and the 2050 wind scenario is shown for the countries with the highest amount of wind and solar capacity.

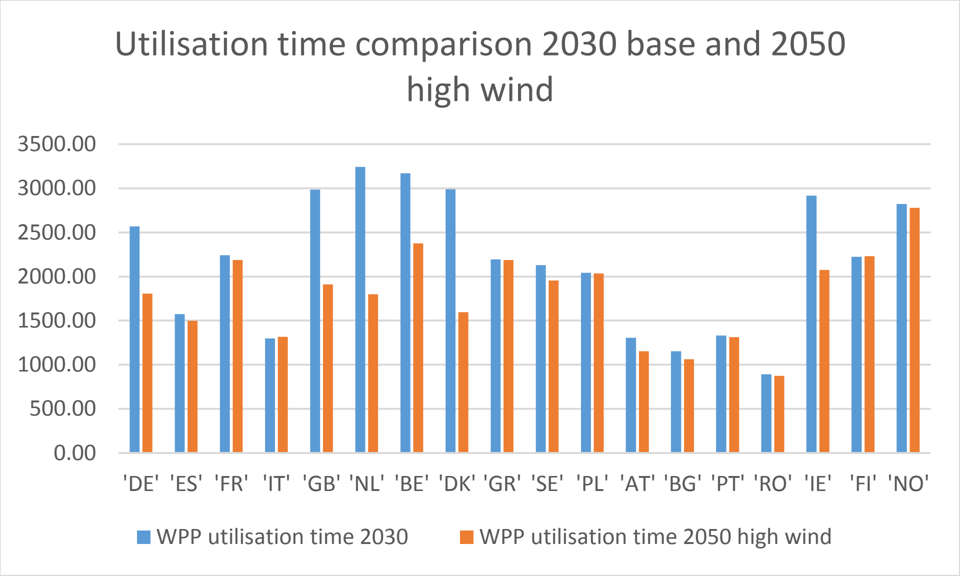


Figure 31, Wind power utilisation in hours

The diagram shows that for many of the countries there are a considerable reduction in the utilisation of the wind power when it is increased to 2050 level.

The countries with the highest reduction in utilisation time are the Netherlands, with a reduction of 1443 hours, Denmark with 1394 hours and Great Britain with 1076 hours. To look closer at how much of this difference that is caused by grid limitations the utilisation difference with infinite and limited grid for the 2050 wind scenario is shown below.

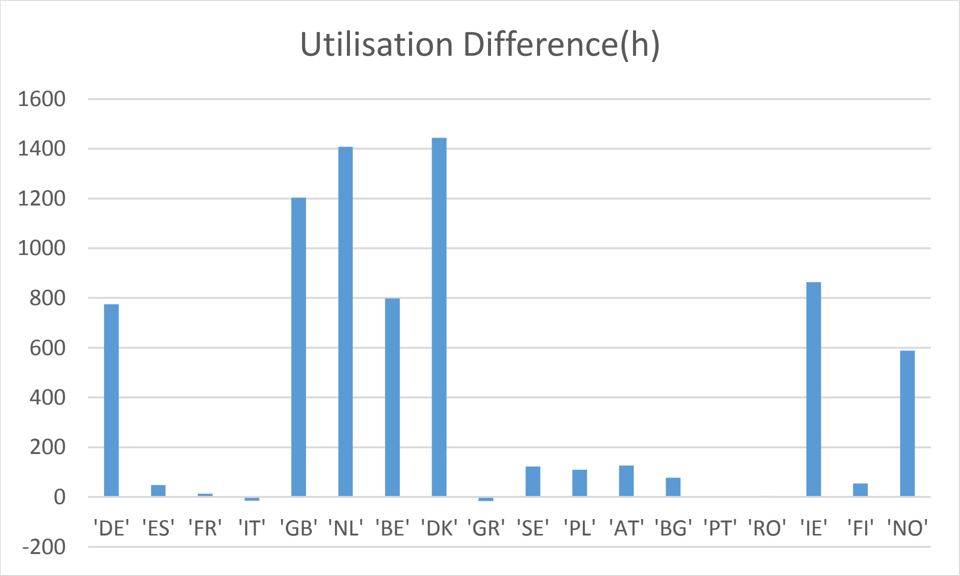


Figure 32 Wind power utilisation(inf grid)-Wind power utilisation(Lim. grid)

When the grid restrictions are removed the highest increase in utilisation is for Denmark, Netherlands and Great Britain. The figure shows that the grid has a much stronger effect on the utilisation of wind with 2050 wind than it had in the 2030 base scenario, where Great Britain was the country who experienced the highest influence of the grid with an increase in utilisation time of 186 hours when the grid limitations were removed. This indicates that more grid investments is necessary if the 2050 goals of renewable energy development should become a reality.

The grid causes the highest reduction in utilisation time in Denmark. In the 2030 Base scenario it was found that the HVDC cable connecting western Denmark, which has the most wind, to Eastern Denmark which has the highest load is almost fully utilized for all hours of the year. Therefore the wind in western Denmark could be better utilized when this cable is infinite. Later in this chapter the hours of congestions between the different countries are shown in a map for the 2050 wind scenario, this map shows that the AC lines between Western Denmark and Germany are the most congested ones. Therefore it is natural that the wind power utilisation in Denmark increase a lot when unlimited power can be transferred to Germany.

Great Britain has a lot of wind power capacity gathered around the Doggerbank area that has to be transported to the main land and to the continent over the HVDC cables. The closeness of the wind farms in Great Britain might lead to a low geographical smoothing of wind power when the grid is limited, the geographical smoothing becomes much stronger when the grid is infinite which might improve the utilisation of wind in Great Britain. Later in this chapter the flow on the HVDC cables are shown for all the scenarios in a map. The map shows that the utilisation of the HVDC cables between Great Britain and other countries are very high, close to hundred percent for many of the cables.

The Netherlands also has a lot of congestions on the AC corridors to the surrounding countries. In addition Netherlands has a lot of its wind power in one large cluster outside the coast giving low geographical smoothing.

Norway has a high reduction in the utilisation of wind power as a consequence of the limitations in the grid, but have only minor changes in utilisation time compared to 2030. The reason why the reduction in utilisation time compared to the 2030 Base scenario is not higher is probably that Norway has three new offshore wind farms in the 2050 wind scenario that was not there in the 2030 base scenario. These wind farms have higher utilisation times than most of the other wind farms in Norway. So even though the grid causes a reduction of utilisation time in Norway that were not present in the 2030 base scenario, the inclusion of the three new offshore wind farms will contribute to increasing the wind power utilisation time. Therefore the overall reduction in utilisation time for the 2050 wind compared to 2030 base scenario is low.

4.2.2 Solar production

The solar power is increased from 202 GW in 2030 to 603 GW in the 2050 solar scenario. As mentioned previously the highest amount of installed solar power in 2030 was found in Germany, Italy, France and Spain. The new solar capacities in these countries are 205.42 GW in Germany, 125.40 GW in Italy, 89.57 GW in France and 72.55 GW in Spain. From these there is a large step down in capacity to the Netherlands that has an installed capacity of 23.89 GW. The increase in solar capacity is totally 400 GW. There is no solar power in Great Britain, so the capacities here will be the same as in 2030. The duration curve for the 2050 solar scenario is shown below together with the duration curve for the 2030 Base scenario.

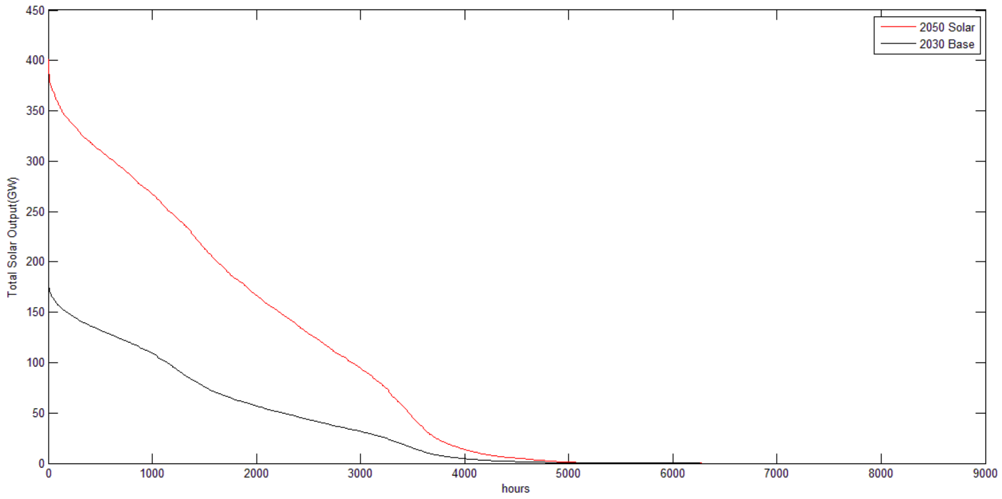


Figure 33, Solar duration curve 2050 solar and 2030 base scenario

The duration curve follows the same trajectory for both scenarios. The total production in 2030 was 275 TWh, which gives an overall utilisation time of 1361 hours, while the total production in the 2050 solar scenario was 714.61 TWh. The overall utilisation time for the 2050 solar scenario is 1185 hours. The maximum solar output for the 2050 solar scenario was 400.9 GW, which is 66.48% of the installed capacity, for comparison the maximum output in 2030 was 90.61% of the installed capacity. The mean production in the 2050 solar scenario was 81.58 GW, which is 13.53% of the installed capacity. In the 2030 base scenario the mean production was 15.59% of the installed capacity.

The total solar production and utilisation for all the scenarios can be seen in the table below.

Scenario	Installed Solar Cap(GW)	Total Solar Prod(TWh)	Utilisation time Lim.grid(h)	Utilisation time Inf. grid(h)
2030 Base	201.95	275.77	1365.52	1371.70
2050 High Solar	603.00	714.61	1185.10	1322.23
2050 High Wind	201.95	254.64	1260.90	1177.65
2050 High Wind and Solar	603.00	584.03	968.54	915.87

Table 16 Solar production and solar utilisation, all scenarios

The utilisation time with limited grid is as expected. It is natural that the utilisation time in the 2050 solar scenario is lower than for the 2030 Base scenario due to the fact that the increased solar influence the grid. This effect might be extra strong because the solar power has its peak production during the summer when the load is lowest. Also it is expected that the 2050 wind scenario has a lower solar utilisation time than the 2030 base scenario in spite of the solar capacities being the same, because the increased wind power will strongly influence the grid and the supply of power. Compared to the 2030 base scenario the decrease in solar utilisation is lower for the 2050 wind scenario than for the 2050 solar scenario even though there is a higher increase in overall production in the 2050 wind scenario. This is logical because the two production sources have very different seasonal and diurnal profile and an increase in solar capacity with a certain amount is expected to influence the solar utilisation time more than the same increase in wind power capacity.

The table shows that for the 2050 wind scenario and the 2050 wind and solar scenario the utilisation time is lower with infinite grid than it is with limited grid.

The utilisation is lower for the 2050 wind scenario than it is for the 2030 base scenario even though the installed solar capacity is the same. The utilisation is also higher for the 2050 solar than it is for the 2050 wind and solar. This happens both with limited and infinite grid, so the increase in grid congestions cannot be the only explanation. This indicates that the solar power are turned off because all the load is supplied for some hours.

Since the solar power seems to be turned off for some hours to create balance between load and supply it should be checked if the total production of wind and solar combined are higher when the capacities are increased and higher with infinite grid than with limited grid.

Scenario	Installed Wind and Solar Cap(GW)	Annual Production Lim. grid(TWh)	Annual production Inf grid(TWh)
2030 Base	546.2	1066.80	1078.43
2050 Solar	947.25	1501.03	1598.72
2050 Wind	1226.85	2130.12	2679.64
2050 Wind and Solar	1627.9	2444.67	2992.17

Table 17 Combined solar and wind production, all scenarios

Table 17 shows that the total production becomes higher and higher as the total capacities are increased. The total production is also always higher with infinite grid than limited grid. This indicates that the reason why the solar utilisation time for the 2050 wind scenario and the 2050 wind and solar scenario are higher with limited grid than with infinite grid might be that the wind and solar potential sometimes exceeds the total load. The load minus the total solar and wind potential are plotted for the 2050 wind and solar limited grid scenario in the figure below.

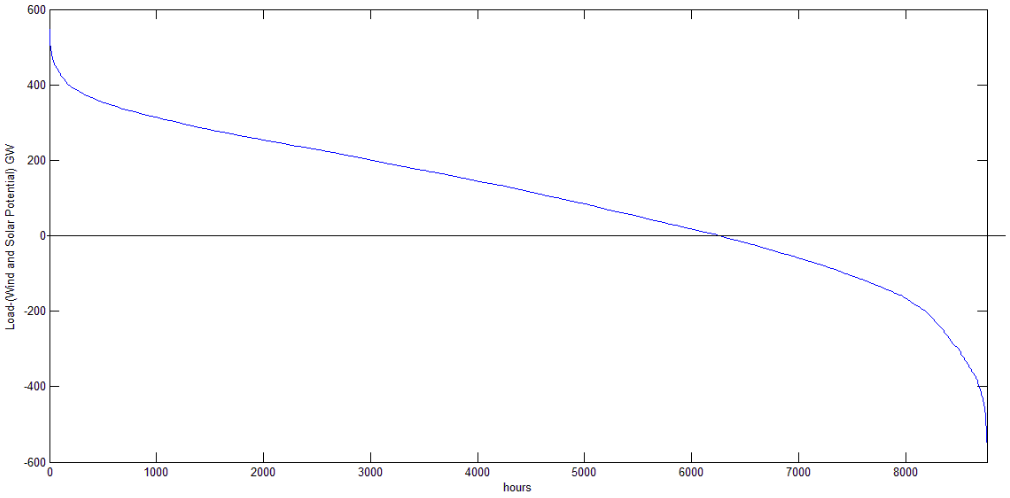


Figure 34 Load minus solar and wind potential, 2050 wind and solar scenario

The figure shows that the wind and solar potential combined exceeds the load for many of the hours. The reason why the solar utilisation with infinite grid is lower than with limited grid must be that during the optimisation the solar is turned off in periods when the wind and solar potential exceeds the demand. It does not matter if it is the wind or the solar production that is turned off since they both have a marginal cost of zero.

Next the solar utilisation for different countries are shown for the 2050 solar and the 2030 base scenario.

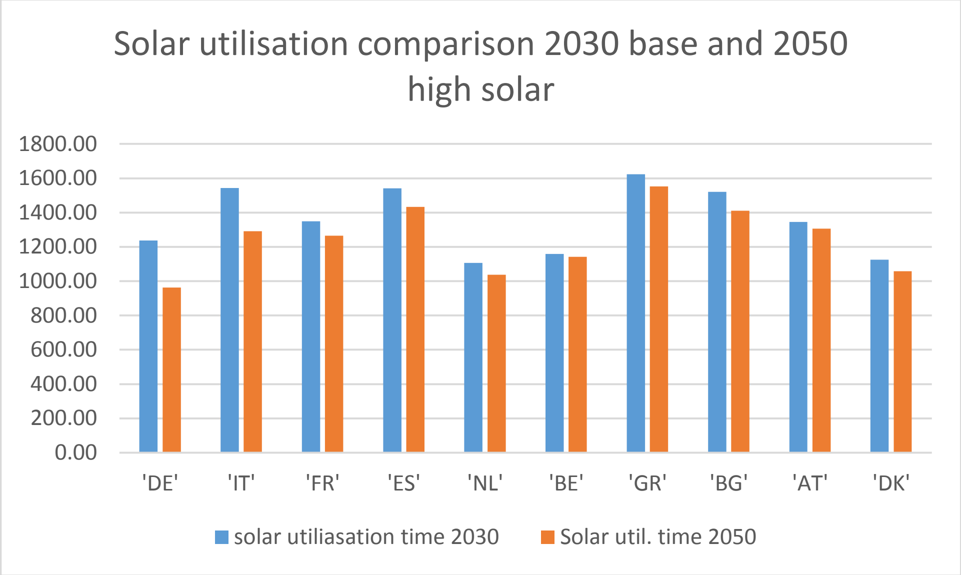


Figure 35, Solar utilisation 2050 solar and 2030 base(h)

Germany and Italy which have the highest capacities of solar has the highest reduction in utilisation time. This is most likely because the grid are most affected in these countries due to the high amount of solar production.

The figure below shows the increase in utilisation with infinite grid compared to limited grid, for the 2050 solar scenario.

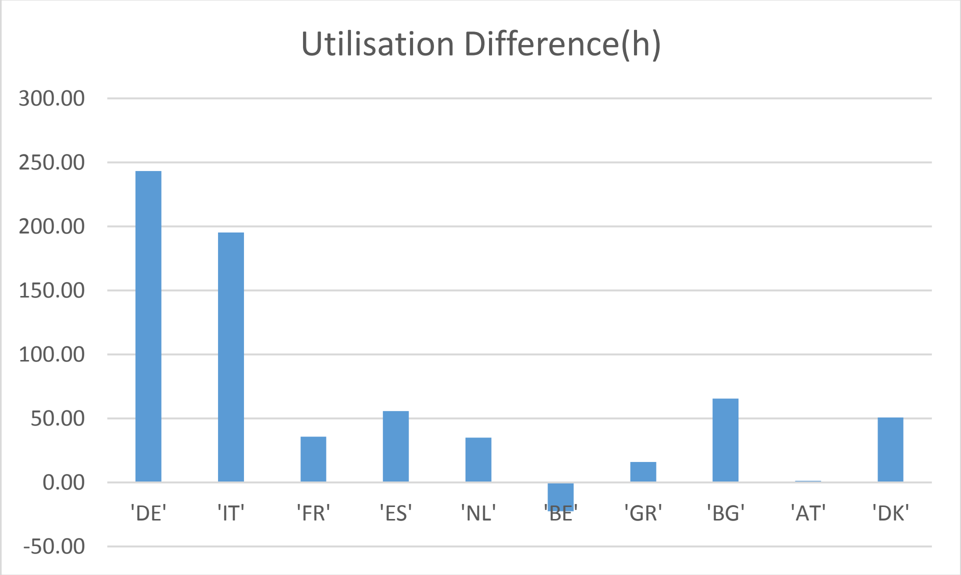


Figure 36, Solar power utilisation(inf grid)-Solar power utilisation(Lim. grid)

The figure shows that the difference is highest for Germany and Italy which has the highest amount of installed solar capacity, which also leads to more congestions. For Germany it can also play an important role that the solar produces the most during the summer when the load is low. Italy does not have the same load pattern due to the need for cooling during the summer. The reduction of utilisation time due to the grid are almost 250 hours for Germany, in the 2030 base scenario the reduction in utilisation caused by the grid was less than 20 hours for all countries. In Belgium the utilisation is lower when the grid is infinite than it is when the grid is limited. This is because the solar power are reduced for some hours in Belgium when the grid is infinite. The solar production with infinite grid minus the solar production with limited grid is shown for Belgium in the figure below.

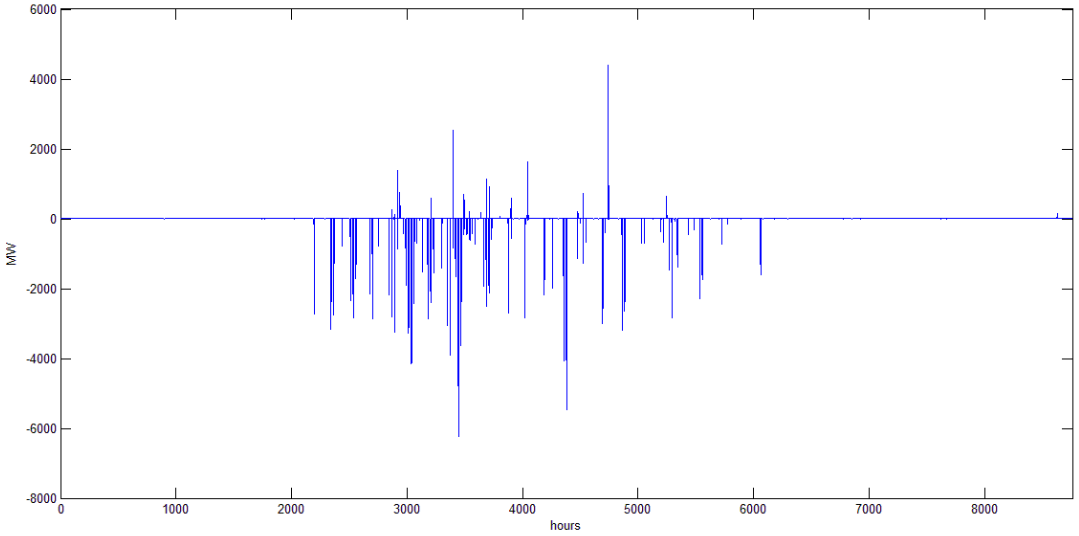


Figure 37 Solar Prod(Inf grid)-Solar Prod(Lim grid) for Belgium

The figure shows that for some of the hours during the summer the solar production is higher with limited grid than it is with infinite grid. Showing that the optimisation causes some of the solar power in Belgium to turn off for some hours to create balance between supply and demand.

4.2.3 Fossil production

When the wind and solar capacity is increased it is expected that the thermal production will decrease. The total amount of installed fossil fuel in 2030 is 442.42 GW. This is not changed in any of these scenarios. The duration curves for the fossil production for all scenarios are shown in the figure below.

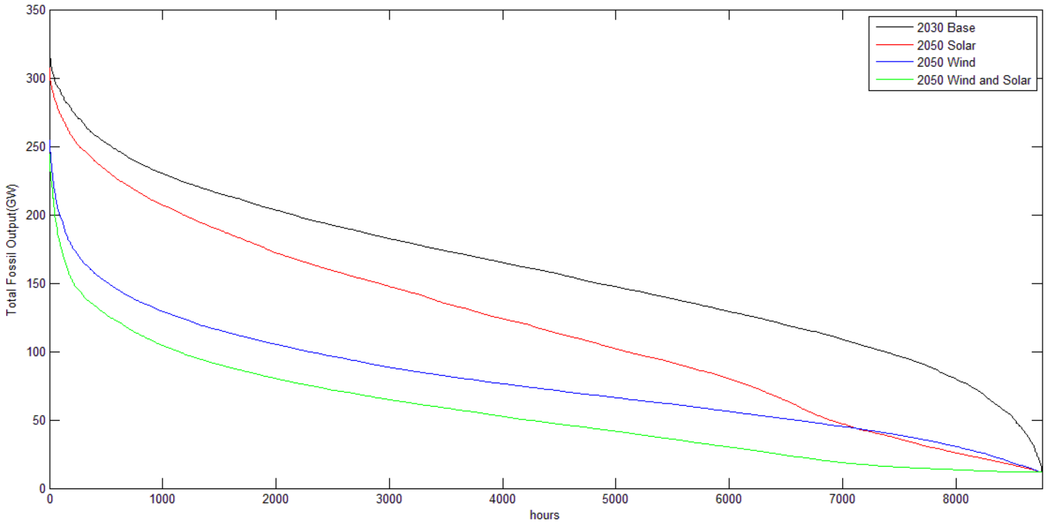


Figure 38 Duration curves, Fossile fuel output, all scenarios

The graphs show that the scenarios that has the same installed wind power has little difference in maximum output. This is because the solar production do not influence the maximum fossil production that much, because the maximum production is in the winter when the solar potential is low. The table below shows the total fossil production and utilisation time for all the scenarios.

Scenario	Total fossil production(TWh)	Utilisation time fossil production(h)
2030 Base	1393.35	3149.4
2050 wind	692.33	1564.9
2050 solar	1041.16	2353.3
2050 wind and solar	489.93	1107.4

Table 18 Fossil production and utilisation, all scenarios

The utilisation of the fossil fuel plants are highest for the 2030 base scenario and decreases as the amount of installed renewable energy increases. The table shows that increasing both wind and solar separately or together will help decrease the amount of power produced from fossil fuel powered plants and therefore also the CO2 emissions.

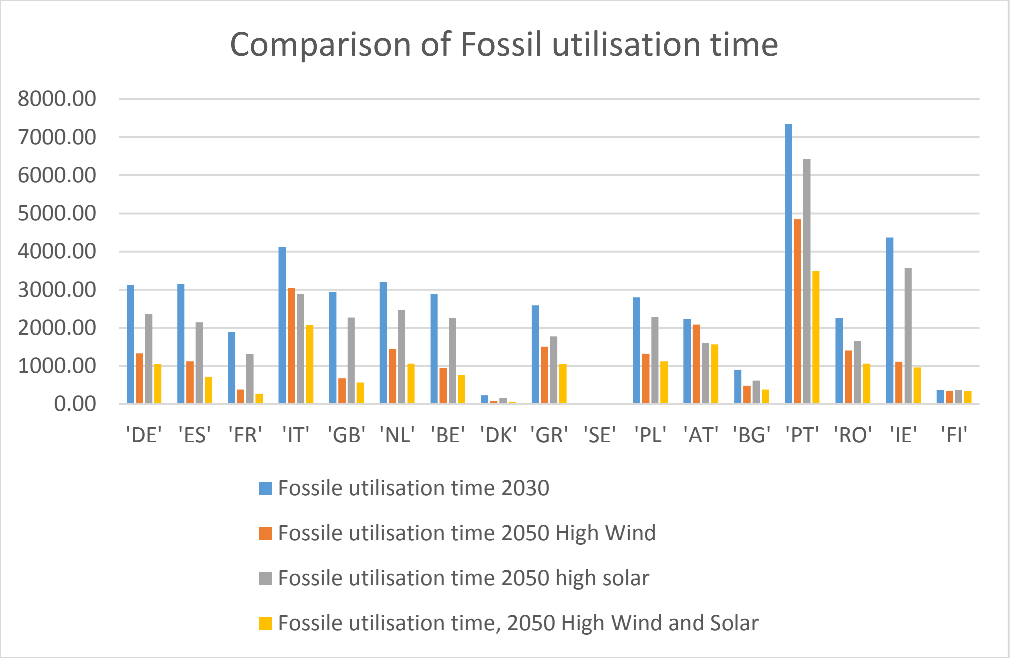


Figure 39, Fossil utilisation time, 2030 Base, 2050 Wind, 2050 Solar and 2050 Wind and solar(h)

The figure shows the same tendency for all the countries, the fossil fuel utilisation is decreased the most when both the wind power and the solar power is increased to 2050 level. It decreases more with increased wind than it does with increased solar, this is because there is more installed wind capacity and the wind has a higher utilisation time. Sweden has 2.1 GW of oil installed, but do not use any of this. The fossil fuel utilisation time in Finland is very low in all scenarios.

For Italy the utilisation of fossil fuel powered plants are higher with high wind than with high solar. This is because the amount of installed solar power in Italy is much higher than the amount of wind. Italy has 125.4 GW solar and only 42.51 GW installed wind in the 2050 scenario. Therefore the increased solar power will lead to a lower need to use fossil fuel than the increased wind.

In the tables below the total production and the utilisation time for the different fossil fuel types are shown. There are four types of fossil fuel powered plants, coal, oil, gas and oil and gas which are mixed fuel plants.

Scenario	Total coal production(TWh)	Utilisation time coal production(h)
2030 Base	364.68	3077.84
2050 Wind	211.91	1788.47
2050 Solar	288.74	2436.93
2050 Wind and Solar	173.54	1464.69

Table 19 Coal production and utilisation, all scenarios

Scenario	Total oil production(TWh)	Utilisation time oil production(h)
2030 Base	0.95	29.94
2050 Wind	0.05	1.68
2050 Solar	0.26	8.06
2050 Wind and Solar	0.01	0.34

Table 20 Oil production and utilisation, all scenarios

Scenario	Total gas production(TWh)	Utilisation time gas production(h)
2030 Base	901.66	3307.02
2050 Wind	389.70	1429.30
2050 Solar	666.33	2443.89
2050 Wind and Solar	259.25	950.87

Table 21 Gas production and utilisation, all scenarios

Scenario	Total oil/gas production(TWh)	Utilisation time oil/gas production(h)
2030 Base	126.06	6484.60
2050 Wind	90.68	4664.36
2050 Solar	85.84	4415.78
2050 Wind and Solar	57.12	2938.40

Table 22 Oil/Gas production and utilisation, all scenarios

The utilisation of the gas plants are higher than for the coal plants in the 2030 base scenario and the 2050 solar scenario, but not for the two scenarios with the wind power capacity increased to 2050 level. This might be because the countries with the highest amount of installed gas is also the countries with the most wind power and less production from the gas power plants are needed in these areas. Coal has a lower marginal cost than gas, but the utilisation of gas is still higher for two of the scenarios. This might be because of the geographical distribution of the gas plants.

There is a very low utilisation of the oil fired plants, there is also a low amount of oil fired plants installed, only 31.84 GW. The reason why the oil fired plants have low utilisation is that they have a very high marginal cost. The utilisation of the oil/gas fired plants is very high even though this is the production source with the highest marginal cost. There is a very small amount of oil/gas fired plants and the high utilisation might be because they are placed where they are most needed.

4.2.4 Nuclear production

Just like the renewable energy sources nuclear power has a low marginal cost. The nuclear production is stable, but the flexibility to produce different amounts of power is very limited. For example the nuclear power plants has a minimum production equal to 20% of the installed capacity. The total amount of installed nuclear power is 105.94 GW. The highest capacity is found in France with 40 GW, then comes Great Britain with 13.91 GW and then Sweden with 10 GW. The table below shows the total nuclear production and the utilisation time for all scenarios.

Scenario	Total nuclear production(TWh)	Utilisation time nuclear production(h)
2030 Base	846.18	7987.39
2050 Wind	717.13	6769.21
2050 Solar	813.27	7676.75
2050 Wind and Solar	655.45	6187.03

Table 23 Nuclear production and utilisation time, all scenarios

The table shows that the utilisation time of nuclear power is high compared to both the renewable production and the fossil production. This is because the nuclear power plants give a very stable production with low marginal costs. The table also shows that the production is highest for the 2030 base scenario and lowest for the 2050 wind and solar scenario, meaning that it is highest for the scenario with the least amount of installed RES and lowest for the scenario with the highest installed RES.

4.2.5 Prices

The figure below shows the mean prices in the countries with the most renewable energy for all the four scenarios.

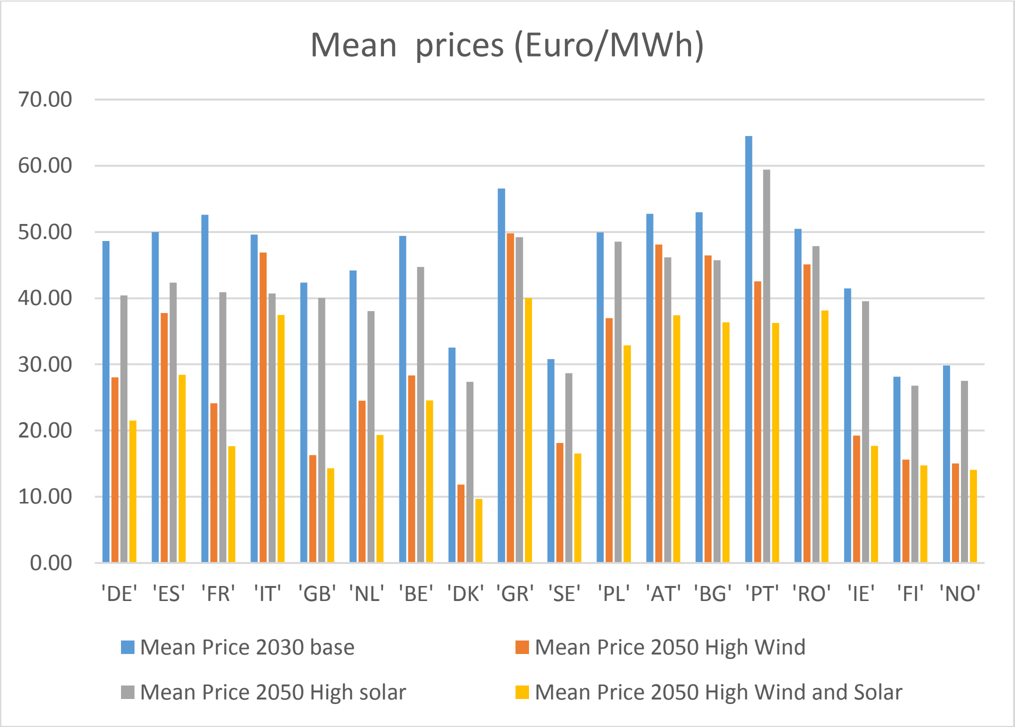


Figure 40, Mean Price, 2030 Base, 2050 Wind, 2050 Solar, 2050 Wind and solar

For most of the countries the variation in price between the four scenarios are the same, the highest price is for the 2030 base scenario, then comes the 2050 solar scenario, then the 2050 wind scenario and at last the 2050 wind and solar scenario that has the lowest price. The prices are highest for the scenarios with the least amount of renewable energy and lowest for the scenario with the highest amount of renewable energy.

However for Italy and also for Greece the variation is a bit different. In those countries the increased solar power influence the price more than the increased wind. For Italy this is natural since the amount of solar power is higher than the amount of wind. Greece have a higher amount of wind than solar, but are connected to Italy which has a higher amount of solar and the other countries surrounding Greece has a low amount of wind.

In the 2030 base scenario the Nordic countries has lower mean price than all other countries, followed by Great Britain. In the 2050 wind and the 2050 wind and solar scenario the mean price in Great Britain is on the same level as the mean prices in the Nordic countries and is actually lower than the mean price in Sweden. This shows that the increased amount of wind power has a strong effect on the prices in Great Britain.

The country with the lowest price when the wind power is increased is Denmark ,with a mean price of only 11.86 Euro/MWh in the 2050 wind scenario and a mean price of 9.67 Euro/MWh in the 2050 wind and solar scenario.

4.2.6 Exchange

In this section the goal is to investigate how the flow on the HVDC corridors between countries are affected of increasing the wind power, the solar power and both the wind and solar power.

First a table showing the utilisation of the HVDC cable and the utilisation in each direction when increasing the wind power to 2050 level is shown. As mentioned in chapter 2 some of the wind farms have split connections, meaning that the wind farm has two HVDC cables connected to two different countries. The transmission capacities on these lines are increased when the wind is increased to 2050 level. When the offshore wind farm capacity in the split wind farms are increased the HVDC cable capacity is increased with the same factor. This influence the HVDC connection between BE-GB, SE-PL, GB-IE and DE-SE. The utilisation of these connections cannot be compared directly between the scenarios with 2030 wind and those with 2050 wind.

Transmission line		Capacity	Utilisation(%)		
From	To		Total	From-To	To-From
NO	GB	1400	95.20	43.71	51.48
NL	NO	1400	99.15	0.46	98.69
DE	NO	1200	94.72	9.46	85.26
NO	DK	1700	66.70	21.22	45.48
NL	GB	1290	95.57	59.20	36.38
BE	GB	9500	51.37	16.56	34.80
FR	GB	5000	89.29	23.92	65.37
SE	PL	2890.8	67.69	64.07	3.62
SE	LV	1000	90.33	68.93	21.39
FI	EE	2000	79.52	73.75	5.77
FR	IE	1000	93.16	36.33	56.83
GB	IE	1460	61.71	25.06	36.65

DE	SE	2678.5	64.47	30.32	34.15
West DK	NL	700	99.05	98.63	0.42
East DK	DE	550	89.44	40.09	49.35
East NO	SE	1100	67.95	45.64	22.31
SE	DK	485	96.63	26.26	70.37
SE	FI	2350	45.98	38.70	7.28

Table 24 HVDC Utilisation 2050 Wind

Next the table showing the utilisation of the main HVDC cable with increased solar

Transmission Line		Capacity	Utilisation(%)		
From	To		Total utilisation	Utilisation From-To	Utilisation To-From
NO	GB	1400	97.77	86.83	10.94
NL	NO	1400	96.27	10.23	86.05
DE	NO	1200	96.20	20.36	75.84
NO	DK	1700	77.15	21.70	55.45
NL	GB	1290	91.71	44.18	47.53
BE	GB	4000	69.40	19.58	49.82
FR	GB	5000	88.34	37.58	50.75
SE	PL	792	76.46	67.44	9.02
SE	LV	1000	97.79	96.79	1.01
FI	EE	2000	95.99	95.66	0.34
FR	IE	1000	93.59	44.25	49.34
GB	IE	763	76.22	13.14	63.07
DE	SE	1486	83.43	18.82	64.60
West DK	NL	700	95.32	91.66	3.66
East DK	DE	550	89.14	65.93	23.20
East NO	SE	1100	85.38	22.43	62.94
SE	DK	485	90.75	47.75	43.00
SE	FI	2350	52.73	50.69	2.04

Table 25 HVDC utilisation 2050 Solar

Last the utilisation of the main HVDC line with increased wind and solar

Transmission Line		Capacity	Utilisation(%)		
From	To		Total	From-To	To-From
NO	GB	1400	93.85	40.19	53.66
NL	NO	1400	96.94	3.24	93.70
DE	NO	1200	92.33	14.22	78.12
NO	DK	1700	65.79	18.21	47.58
NL	GB	1290	95.79	64.54	31.25
BE	GB	9500	52.29	22.46	29.83

FR	GB	5000	90.05	31.43	58.62
SE	PL	2890.8	67.79	64.92	2.87
SE	LV	1000	90.55	69.61	20.94
FI	EE	2000	79.66	73.51	6.15
FR	IE	1000	93.96	42.76	51.19
GB	IE	1460	61.69	26.45	35.24
DE	SE	2678.5	68.86	41.75	27.11
West DK	NL	700	98.44	95.83	2.61
East DK	DE	550	91.16	36.72	54.44
East NO	SE	1100	64.92	41.38	23.53
SE	DK	485	97.04	20.53	76.50
SE	FI	2350	51.58	45.28	6.29

Table 26 HVDC utilisation 2050 Wind and Solar

Three maps are drawn to illustrate the main flows in the grid. They show the utilisation and the main direction of flow. The map for the 2050 wind scenario is shown below. The arrows and numbers in grey are for the 2030 base scenario. The arrows closeness to a given node shows the percentage of the total utilisation that is in the direction of the arrow. The flow is shown by a bidirectional array in the cases where the utilisation in none of the directions are more than 60 % of the total utilisation.

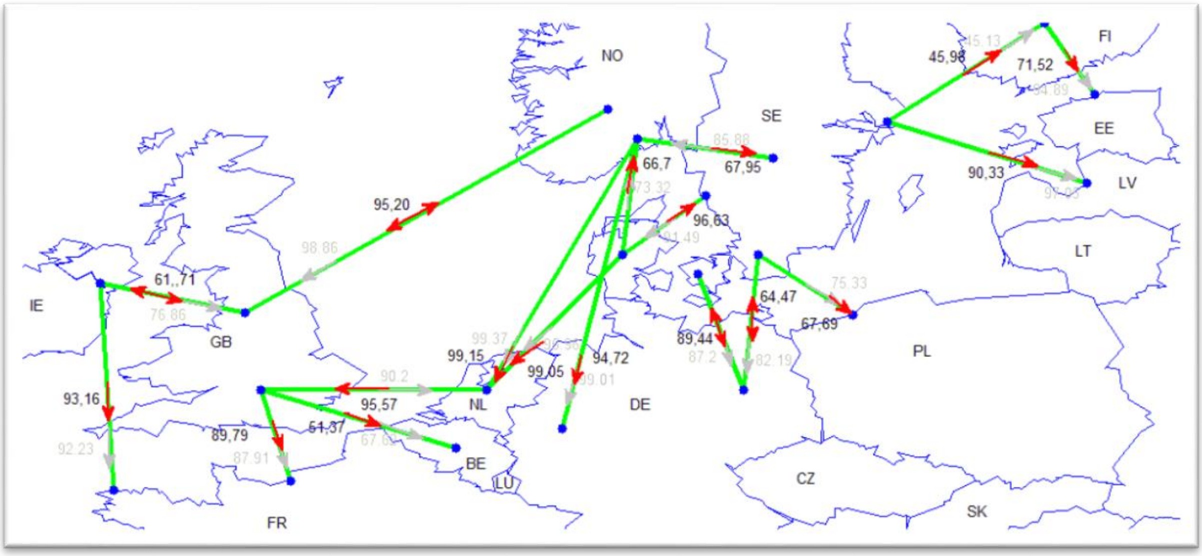


Figure 41, Map 2050 Wind, HVDC flow directions, total utilisation shown in black(%)

The map shows that the flow between Norway and Great Britain has changed totally with 2050 wind compared to the 2030 base scenario. In the 2030 base scenario the flow was almost entirely from Norway to Great Britain, with 2050 wind the flow is bidirectional. The utilisation of the HVDC cable in the direction from Great Britain to Norway is actually 51.48 percent while the utilisation in the opposite direction is only 43.71 percent. To understand why there is more flow from Great Britain to Norway than from Norway to Great Britain like it was in the 2030 base scenario the price variation throughout a year for both Norway and Great Britain are drawn in the graph below.

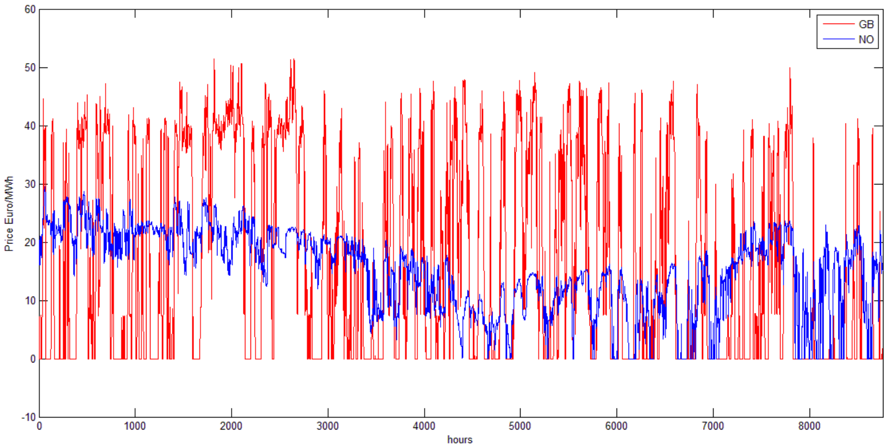


Figure 42, Price variation Great Britain and Norway(Euro/MWh) in the 2050 wind scenario

The prices in Great Britain are much more variable than in Norway due to the high amount of wind power, and is actually zero for many of the hours. Especially during the winter when the prices in Norway are at its highest and the prices in Great Britain some times are zero there will be a high incentive to export as much as possible to Norway. The total utilisation of the cable has decreased from 98.86 % in the 2030 base scenario to 95.20% in the 2050 wind scenario.

The flow on the cable from Norway to the Netherlands is almost exactly the same as in the 2030 scenario. The cable is still close to a hundred percent utilized and almost all of the flow is from Norway to the Netherlands, just like in the 2030 base scenario. The reason why the flow does not change much might be because Norway has a high increase in offshore wind because of the three new offshore wind farms that are added in the 2050 scenario. Therefore the high increase in wind power capacity in Netherlands and the surrounding countries does not make more of the flow go from Netherlands to Norway.

The utilisation of the cable between Norway and Germany has decreased a bit and the utilisation of the cable in the direction from Norway to Germany has decreased compared to the 2030 base scenario. In the 2030 base scenario the total utilisation was 99.01%, this has decreased to 94.72% in the 2050 wind scenario. In the 2030 base scenario the utilisation of the cable from Germany to Norway was 7.22 %, this has increased to 9.46% in the 2050 wind scenario. This is natural since Germany is the country with the highest amount of installed wind power and therefore more of the transmission will go from Germany to Norway.

The HVDC cables between Great Britain and the continent were used mostly for export from Great Britain to the continent in the 2030 base scenario. In the 2050 wind scenario they are used almost equally as much for import from the continent to Great Britain. An example of this is the exchange between Great Britain and France. The utilisation of the 5000 MW HVDC capacity in the direction from France to Great Britain has increased from 12.37 % in the 2030 base scenario to 23.92 %in the 2050 wind scenario.

The flow on the line between Great Britain and the Netherlands has higher utilisation from the Netherlands to Great Britain in the 2050 wind scenario compared to the 2030 base scenario. The utilisation was only 33.07% in the 2030 base scenario this had increased to 59.2 % in the 2050 wind scenario. The flow between Great Britain and the continent generally is more bidirectional when the wind is increased to 2050 level than in the 2030 scenario. This is in spite of the mean price being considerably lower in Great Britain than in the continental countries. This can be explained by the high price variations due to the high amount of installed wind power, which will cause the prices in Great Britain to be lower than the price in the continent for some hours and higher in others, giving more bidirectional exchange.

Looking at the exchange from Germany to Norway, Denmark and Sweden the general tendency is that the utilisation of the cable from Germany to the Nordic countries has increased. This is in spite of the fact that the mean prices in Germany still is considerably higher than in the Nordic countries. The reason for the higher exchange from Norway to the continent is the high variation of the increased amount of wind power.

The map showing the main flows on the HVDC connections for the 2050 solar scenario is shown below.

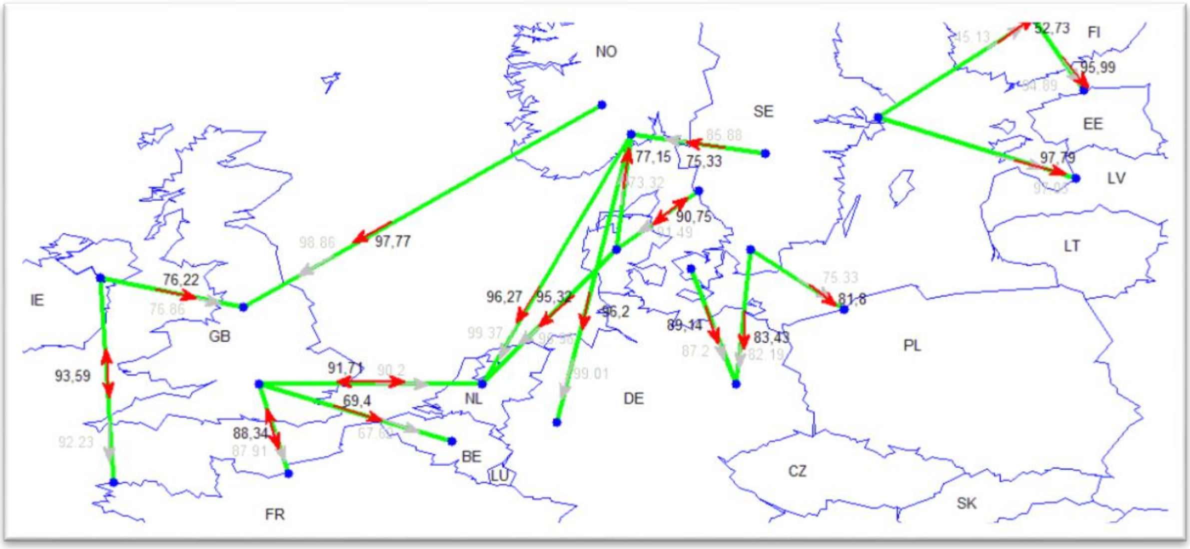


Figure 43, Map 2050 Solar, HVDC flow directions, total utilisation shown in black(%)

Looking at the flow between Norway and Great Britain the map shows that a lower percentage of the utilisation is from Norway to Great Britain than in the 2030 base scenario. In the 2030 base scenario the utilisation of the HVDC cable from Norway to Great Britain was 91.51 %, in the 2050 solar scenario this has decreased to 86.83%. At the same time the utilisation of the line from Great Britain to Norway has increased from 7.35% in the 2030 base scenario to 10.94% in the 2050 solar scenario

The map shows that Great Britain exports less and imports more from the continent than in the 2030 Base scenario. In the 2030 scenario the utilisation of the HVDC connection from Great Britain to France was 75.53 percent, with 2050 solar this has decreased to 50.75%. While the utilisation of the cable from France to Great Britain has increased from 12.37% in the 2030 base scenario to 27.58% in the 2050 solar scenario. This is not surprising since Great Britain has no increase in capacity for this scenario and France is one of the countries with the highest amounts of installed solar capacity. The cables from Great Britain to Belgium and Netherlands also have a lower percentage of export from Great Britain compared to the 2030 base scenario. This is because the solar capacity in both of these countries has increased and that there is a general increase in solar capacity on the continent.

There is less export on the HVDC cables from Norway to the continent with 2050 solar than it was with the 2030 base scenario. In the 2030 base scenario the utilisation of the HVDC cable from Norway to Germany was 91.79 %, this has decreased to 75.84% in the 2050 solar scenario. The utilisation from Norway to the Netherlands was 98.85% in 2030, this has decreased to 86.05% in the 2050 solar scenario. On most of the cables there are only minor changes in the overall utilisation of the cable. The reason why the export from Norway to the continent has decreased is that there is no solar power in Norway and the continental countries have the highest share of solar power.

The export from Sweden to Poland, Finland and Latvia has increased. In addition to an increase in the relative utilisation from Sweden, the overall utilisation of these HVDC lines has increased. This is because there is less export on the lines from Sweden to Germany, Denmark and Norway than in the 2030 base scenario. This leaves more of the capacity free to be exported east. The utilisation of the cable from Sweden to Germany has decreased because Germany is the country with the highest increase in solar power and therefore needs less import. The reason why the export from Sweden to Norway and Denmark has decreased might be that Norway and Denmark has less export to the continent than in the 2030 base scenario.

The utilisation of the cables between Denmark and Sweden and Denmark and Norway has increased in the direction from Denmark. This is because Denmark exports less to Germany and the Netherlands than in the 2030 base scenario due to the higher amount of solar power in these countries.

The map of the HVDC flow for the 2050 wind and solar scenario are shown below.

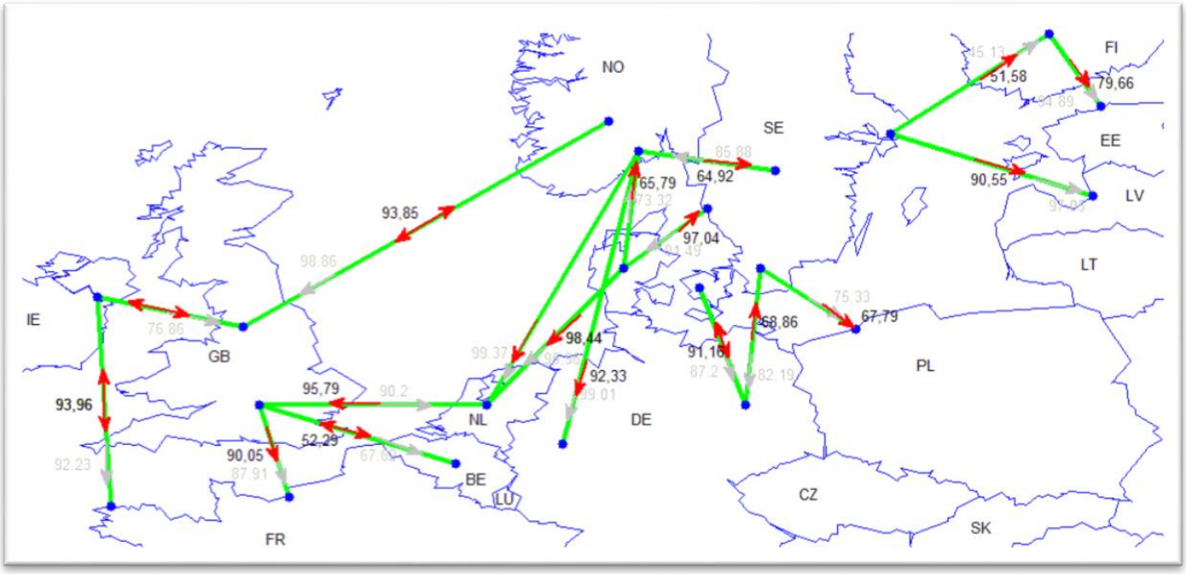


Figure 44, Map 2050 Wind and Solar, HVDC flow directions, total utilisation shown in black(%)

The flow between Norway and Great Britain is very similar to the flow with 2050 wind scenario and is bidirectional because of the higher amount of wind in Great Britain compared to the 2030 base scenario. The utilisation of the lines from Great Britain to the continent is very similar to the 2050 wind scenario except that a lower percentage of the utilisation is from Great Britain to the continent than with the 2050 wind scenario. This is natural since it is Germany, France and Italy that has the highest amount of installed solar power. For example the utilisation from Great Britain to France was 65.37% in the 2050 wind scenario this has decreased to 58.62 % in the 2050 wind and solar scenario.

The utilisation from Germany to Norway has increased compared to the 2030 base scenario. In the 2030 base scenario the utilisation was only 7.22%, this has increased to 14.22% in the 2050 wind and solar scenario. The utilisation from Germany to Norway is higher than for the 2050 wind scenario, but lower than for the 2050 solar scenario, where it was 20.36%. The utilisation of the cable from the Netherlands to Norway shows the same tendency. The utilisation was 0.51% in the 2030 base scenario, 0.46% in the 2050 wind scenario and 3.24% for the 2050 wind and solar scenario, while the utilisation in the 2050 solar scenario was 10.23%, which is much higher than for the other scenarios. The reason for this might be that the increase in solar capacity almost exclusively influence the continental countries and not the Nordic countries, while the wind power influence both.

Exchange between Norway and Germany

In this section the exchange between Norway and Germany are investigated further for the 2030 base scenario, the 2050 wind scenario and the 2050 solar scenario. The figure below shows the flow from Germany to Norway during the day.

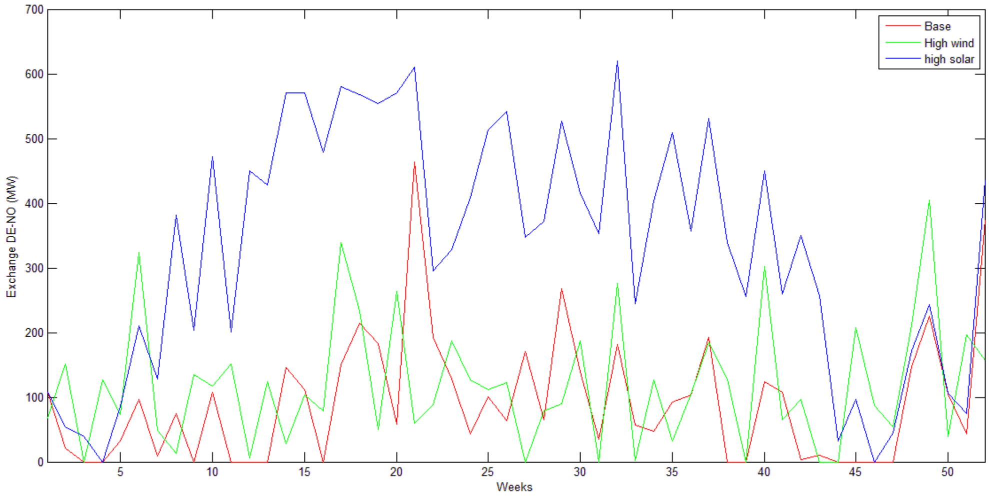


Figure 45 Exchange Germany- Norway during day, for 2030 base, 2050 wind and 2050 solar scenario,

The figure shows that the exchange from Germany to Norway is highest for the 2050 solar scenario. The exchange follow the seasonal variation of solar power, with high exchange during the spring and summer and low exchange during the winter. The reason why the exchange is higher in the spring than in the summer might be that the reservoir levels are lower in the spring than in the summer. This will give lower prices in Norway during the summer and less available hydro storage.

The figure below shows the exchange from Germany to Norway during the night.

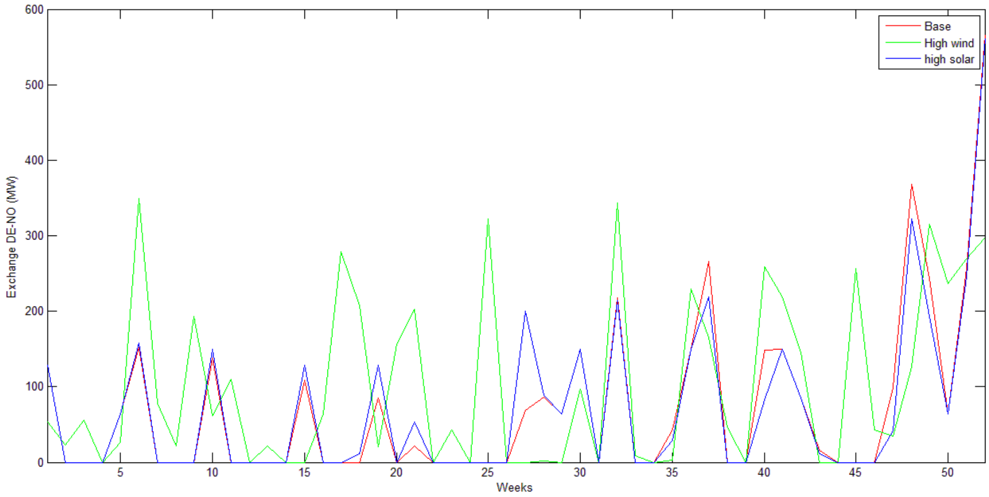


Figure 46 Exchange Germany-Norway during night, for 2030 base, 2050 wind and 2050 solar scenario

During night the exchange is highest for the 2050 wind scenario. This is because there is no solar production during night and the exchange for the 2050 solar scenario is therefore quite similar to the 2030 base scenario. The figure below shows the flow from Norway to Germany during the day.

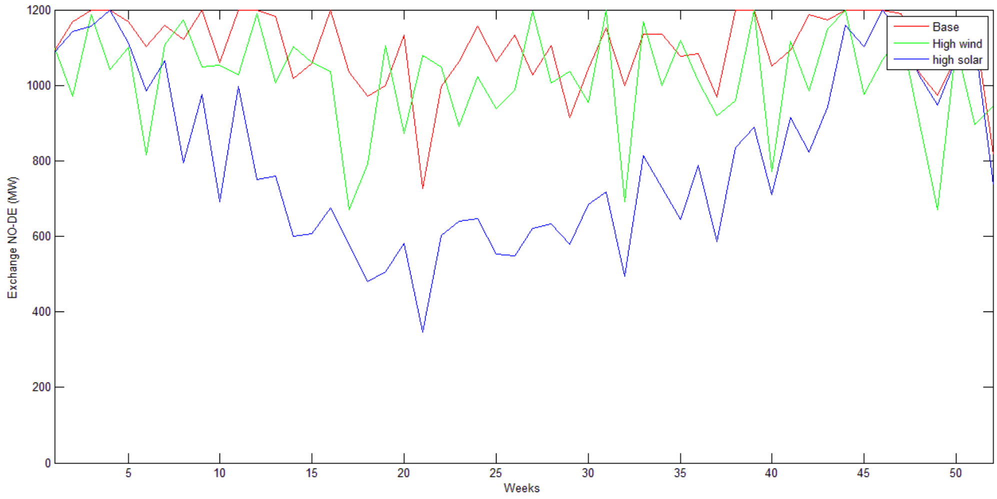


Figure 47 Exchange Norway-Germany during day, for the 2030 base, 2050 wind and 2050 wind and solar scenario

For the 2050 solar scenario the exchange follows the pattern in solar radiation throughout a year, the flow from Norway to Germany is lowest during the summer when the solar radiation is strongest. This is because less power is needed in Germany due to the high amount of installed solar power. The figure below shows the exchange during night from Norway to Germany

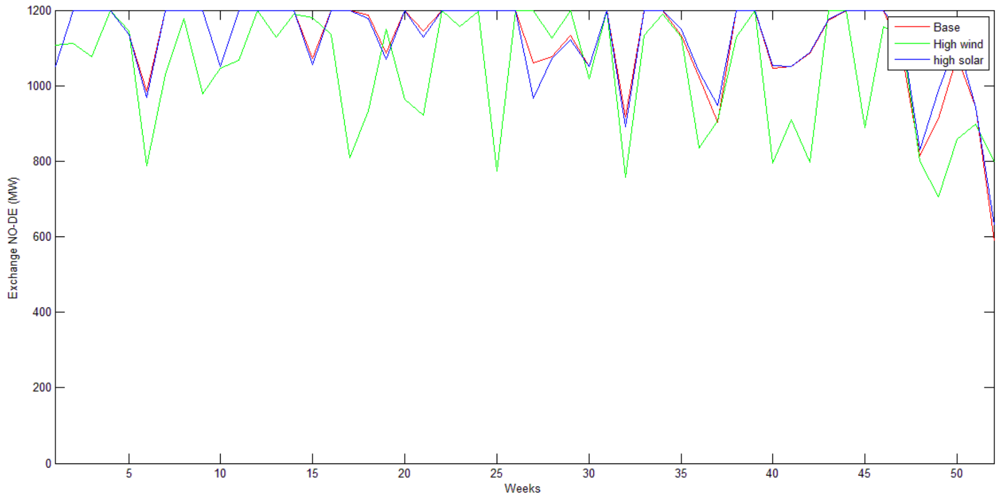


Figure 48 Exchange Norway-Germany during night, for the 2030 base, 2050 wind and 2050 wind and solar scenario

In this case there is no solar radiation, so the 2050 solar scenario has a very similar flow as the 2030 base scenario. The 2050 wind scenario has a lower amount of export from Norway to Germany than the other two scenarios at night. This is caused by the high amount of wind power in Germany and that less import is needed.

4.2.7 AC congestions

So far, the focus has been on the exchange over the HVDC cables, now the focus is on the congestions seen on the AC corridors between countries. In the 2030 base scenario the eleven most congested lines was shown in the map in Figure 24. The map below shows the congestions in the 2050 wind scenario. The same borders that was included in the 2030 base scenario are drawn, in addition the other borders that appear among the eleven most congested borders are also included. For the 2050 wind scenario, this was the border between Germany and Switzerland. This shows that it to a large extent is the same corridors that are congested when the wind is increased to 2050 level.

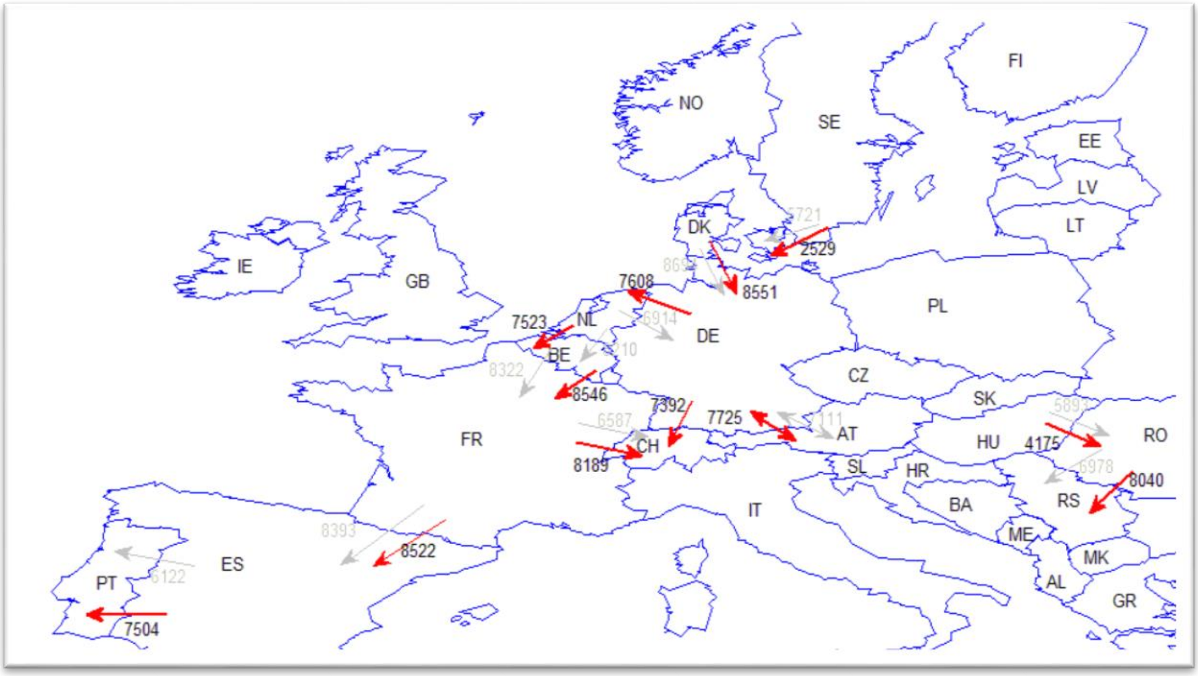


Figure 49, Main congestion, 2050 wind

The corridor between Germany and Denmark is still the most congested one as it was in the 2030 base scenario. With 2050 wind the hours of congestions from Denmark to Germany has decreased from 8694 to 8001 hours, but the hours of congestions from Germany to Denmark has increased from 65 to 550, the total number of congested hours in the 2050 wind scenario is 8551. In the 2030 base scenario the total number of congested hours was 8694. This shows that the high increase of wind in Germany and many of the surrounding countries causes a higher export of power from Germany to the Nordic countries, and therefore more strain on the AC lines connecting the Nordic countries to the continent.

The flow between East Denmark and Sweden has decreased a lot compared to 2030 base scenario. In the 2030 base scenario there was 5721 hours of congestion, with 99.52% of these hours being in the direction from Sweden to East Denmark. In the 2050 wind scenario this has decreased to 2529 hours with 75 % of the hours being in the direction from Sweden to East Denmark. This is due to the lower export of power from the Nordic countries to the continent, since Eastern Denmark shares a border with Germany.

The direction of the congestions has changed between Germany and the Netherlands. In 2030 there was a total of 6914 hours of congestions and 68.8 percent of these were from the Netherlands to Germany. In the 2050 wind scenario the total number of hours with congestions has increased to 7608 and 74.4 percent of these are from Germany to the Netherlands. The reason for this cannot be found in the mean price, because the mean price is higher in Germany in both the 2030 base scenario and the 2050 wind scenario. The difference between the mean price in Germany and in Netherlands is also similar for both scenarios. The reason for the change of direction of the congestions must therefore be found by looking at the price variation in the two countries throughout the year. The graph below shows the price in Germany minus the price in the Netherlands for the whole year.

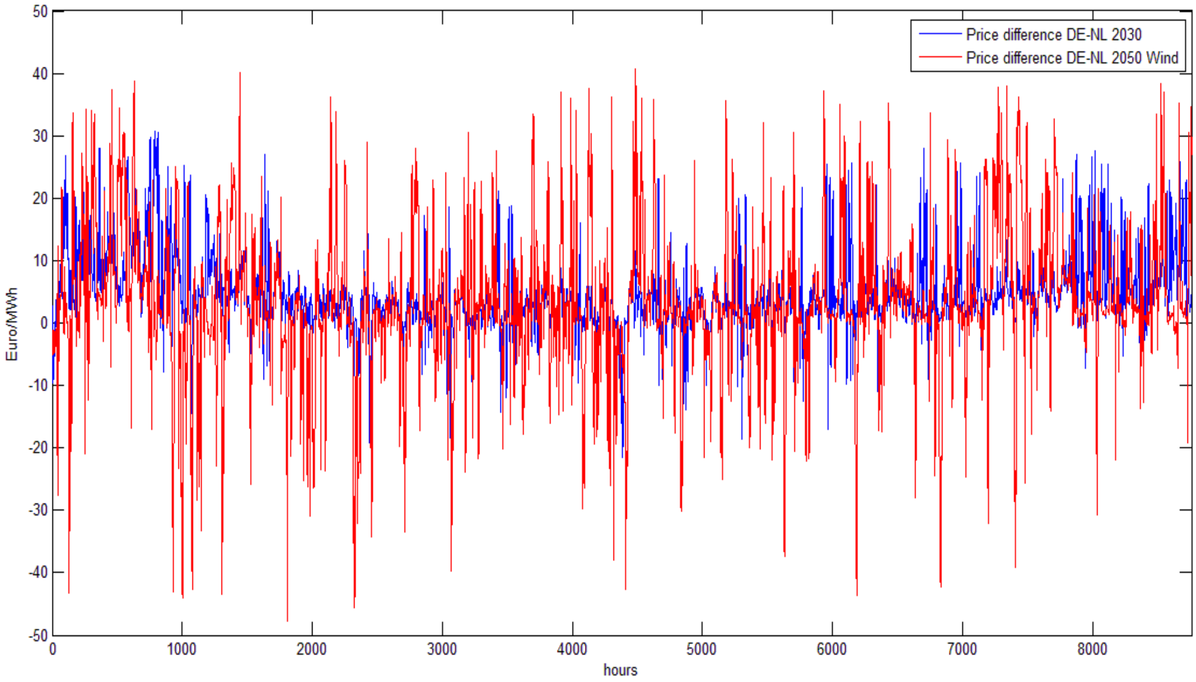


Figure 50 Price difference between Germany and the Netherlands.

When the price difference is negative it means that the price is higher in the Netherlands than in Germany, which would indicate that the flow of power should be from Germany to the Netherlands. The graph shows that the price difference is much more variable and usually higher in the 2050 wind scenario than in the 2030 base scenario, this is caused by the large increase in variable wind power.

For the 2050 wind scenario the graph shows very high negative price differences for many hours of the year, indicating that the flow is from Germany to the Netherlands.

Next the congestions for the 2050 solar scenario is shown. Three more borders are added to the map because they were among the 11 most congested, these are the borders between France and Italy, Switzerland and Austria and Switzerland and Italy.

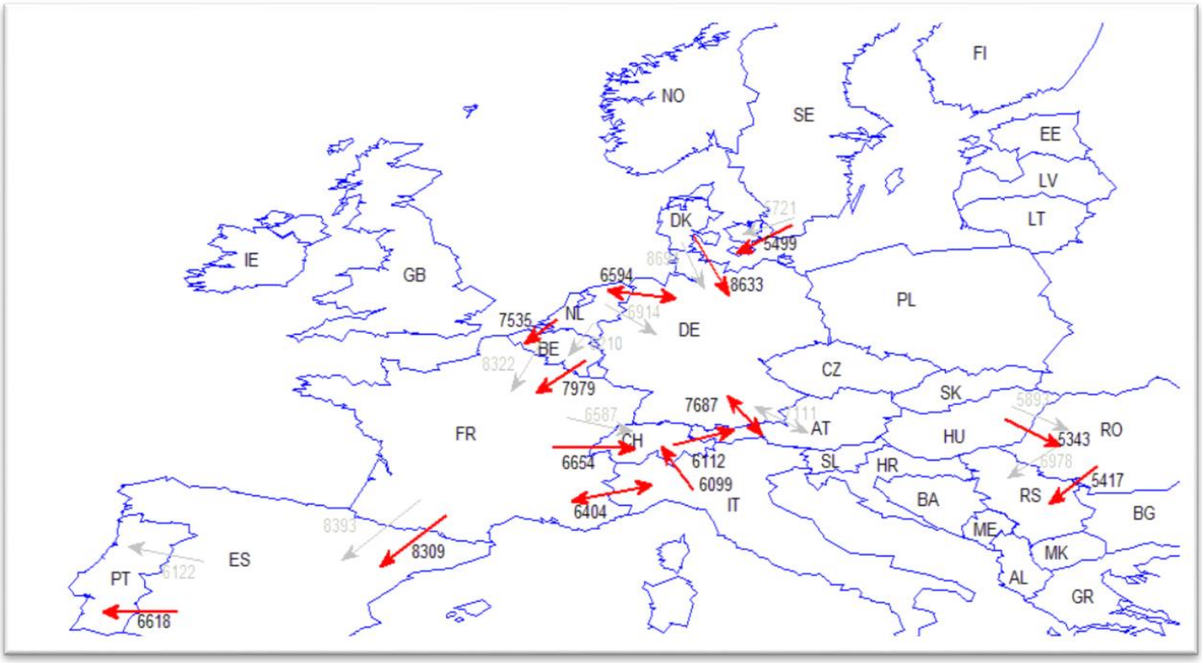


Figure 51, Main congestions 2050 Solar

The map shows that it is still the line between Denmark and Germany that is the most congested one. The total number of hours of congestion has decreased a bit over this border, but the number of hours from Germany to Denmark has increased from 65 in the 2030 base scenario to 680 in the 2050 solar scenario. This is because Germany is the country with the highest amount of solar power and therefore exports more to Denmark.

The number of hours with congestions over the border between France and Italy has increased. In the 2030 base scenario there was a total of 4871 hours of congestions on this border. 59% of these being from Italy to France. The number of hours with congestions in the 2050 solar scenario is 6404, 52 percent of these being in the direction from France to Italy.

The congestions between Switzerland and Austria has increased, and so has the congestions between Switzerland and Italy. Switzerland has zero installed solar power, Austria has 3.5 GW in 2030, Italy had 42 GW of installed solar power in 2030 which is close to tripled in the 2050 solar scenario. In 2030 the total hours of congestions between Switzerland and Austria was 4881 hours, 78.73 percent of this being in the direction from Switzerland to Austria. In the 2050 solar scenario this has increased to 6112 hours, 63.4 percent of these being from Switzerland to Austria. It is the hours of congestions from Austria to Switzerland that has increased the most compared to the 2030 base scenario. This is most likely caused by the fact that Austria has 3.5 GW of installed solar power, and therefore more power available for export. In the 2030 base scenario the total hours of congestions between Switzerland and Italy was 4843 hours, 84.16 percent of these being from Italy to Switzerland. In the 2050 solar scenario this has increased to 6099 hours, with 75.5 percent of these being from Italy to Switzerland. The total hours of congestions from Italy to Switzerland has increased from 4076 to 4607 in 2050 solar. This is caused by the higher amount of solar power in Italy. Also the hours of congestions from Switzerland to Italy has increased in 2050 solar compared to the 2030 base scenario.

A higher percentage of the hours with congestions are from Germany to Netherlands in the 2050 solar scenario compared to the 2030 base scenario. In the 2030 base scenario 68.8 percent of the hours with congestions was from the Netherlands to Germany, in the 2050 solar scenario this had changed to 54 percent of the hours. This is caused by the very high increase in solar power in Germany, and the fact that Netherlands has transmission capacity to both Great Britain and the Nordic countries which has a low amount of solar power.

The congestions between France and Italy has increased in the 2050 solar scenario compared to the 2030 base scenario.

The congestions for the 2050 wind and solar scenario is shown below.

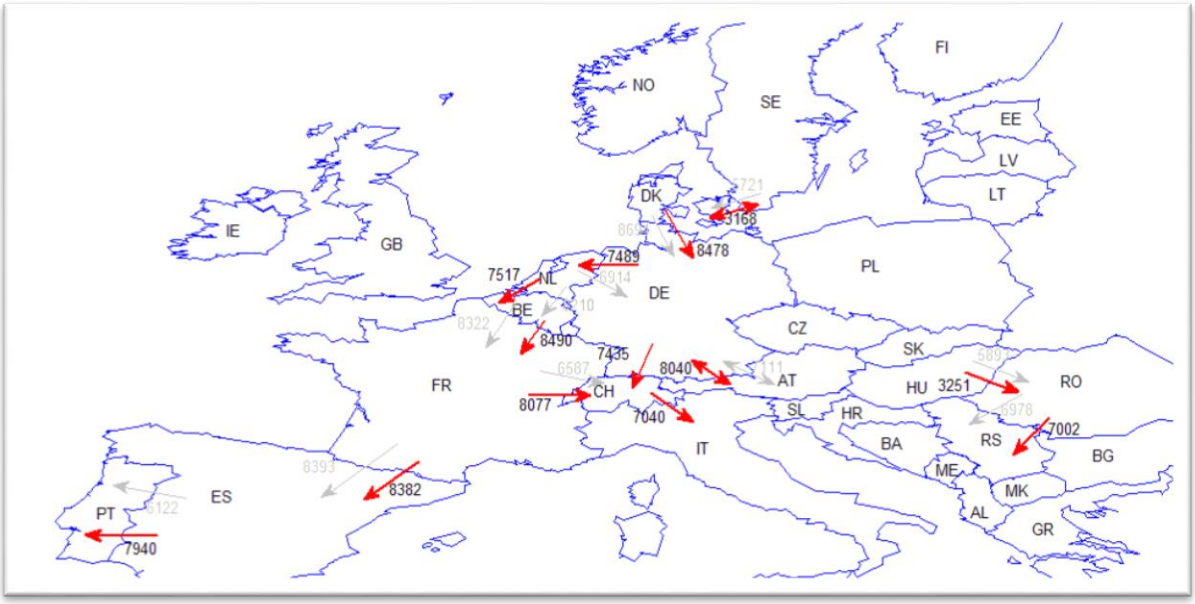


Figure 52, Main congestions 2050 Wind and Solar

In the 2050 wind and solar scenario the border between Denmark and Germany is no longer the most congested border, but the second most congested. The most congested border is between Belgium and France. This is because the number of hours with congestions have increased from France to Belgium, which is caused by the high increase in both wind and solar in France. In the 2030 base scenario the border between Denmark and Germany was the most congested one, with a total of 8694 hours, with 99.25% of these being from Denmark to Germany. In the 2050 wind and solar scenario the total hours of congestions over this border had decreased to 8478 hours, with 88.14 percent of these being from Denmark to Germany. The hours of congestions from Denmark to Germany has decreased, while the hours of congestions from Germany to Denmark has increased. This indicates the same tendency of exchange that was found in the HVDC flow map, where the exchange pattern no longer goes only from the Nordic countries to the central European countries, but that the high amount of RES in the central European countries causes the flow to go in both directions.

The map shows that the congestions over the border between Germany and the Netherlands has changed direction. In the 2030 base scenario most of the congestions were from the Netherlands to Germany. In the 2050 wind and solar scenario the highest percentage of congestions were from Germany to the Netherlands. In the 2030 base scenario the total hours of congestions were 6914 hours with 68.8% of these being from Netherlands to Germany. In the 2050 wind and solar scenario the total hours of congestions has increased to 7489 hours, with 80.5 % being from Germany to the Netherlands. In both the 2050 wind and the 2050 solar scenarios the hours of congestions were bidirectional, indicating that the combination of increased wind and solar power has a strong effect on the flow between these countries. The combination of the high amount of wind and solar in Germany increases the export to the Netherlands. Also the export from Netherlands to Great Britain are substantially higher in the 2050 wind and solar scenario than in the other scenarios, showing that the increased solar and wind production in Germany are exported further to Great Britain.

The number of congested hours for the border between Switzerland and Italy has increased compared to the 2030 base scenario. In the 2030 base scenario the border between Switzerland and Italy was congested for 4843 hours, with 84.16% being from Italy to Switzerland. In the 2050 wind and solar scenario this had increased to 7040 hours, with 68.4% being from Switzerland to Italy. This is different from the 2050 solar scenario when a higher percentage of the hours with congestions were from Italy to Switzerland. Looking at the hours of congestions from France to Switzerland and from Germany to Switzerland these have increased, especially in the direction to Switzerland. This shows that Switzerland imports more from Germany and France which have a high increase in both wind and solar power, and therefore Switzerland exports more to Italy than in the other scenarios.

4.2.8 Congestion costs

Next the total congestions costs are found. The figure below shows the costs for all the scenarios with limited grid, infinite grid and the difference between them that is the bottleneck costs.

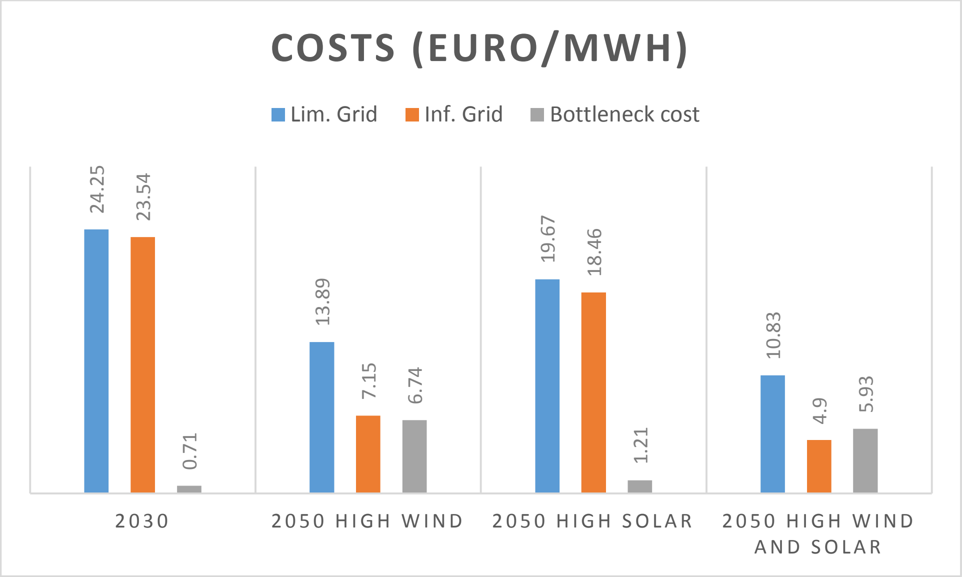


Figure 53, Total costs, 2030 base, 2050 Wind, 2050 Solar and 2050 Wind and solar

The diagram shows that the costs both with infinite and limited grid are highest for the 2030 base scenario, then comes the 2050 solar scenario, then the 2050 wind scenario and at last the 2050 wind and solar scenario. This is natural since this is the order the scenarios would take if they were sorted from the scenario with the least amount of renewable energy to the scenario with the highest amount of renewable energy. The table below shows only the bottleneck costs.

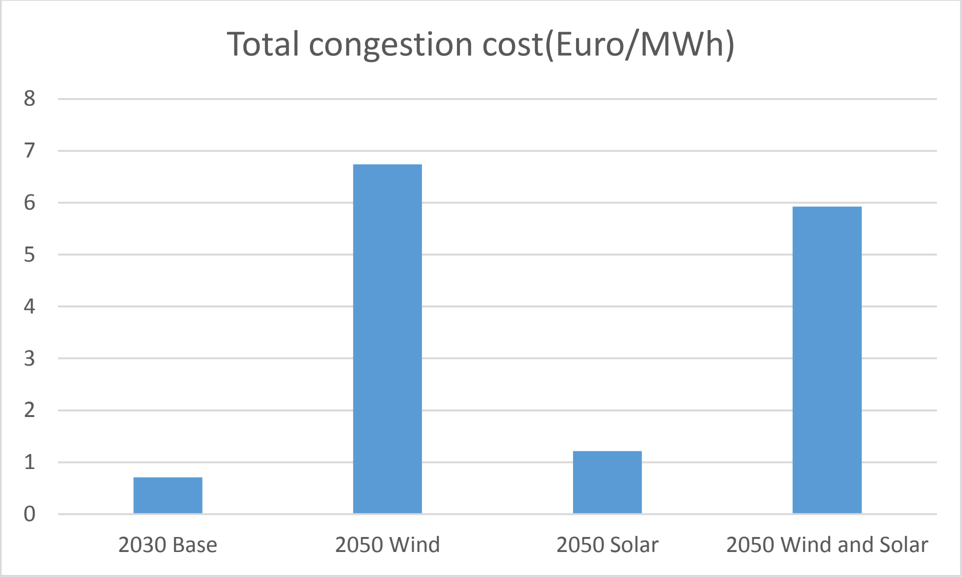


Figure 54, Total congestion costs, 2030 base, 2050 Wind, 2050 Solar and 2050 Wind and Solar

The bottleneck costs are lowest for the 2030 base scenario, meaning that this is the scenario where the grid contributes the least to increasing the costs. When the solar is increased to 2050 level the bottleneck costs increase from 0.71 Euro/MWh to 1.21 Euro/MWh. When the wind is increased to 2050 level the bottleneck costs increases a lot more, from 0.71 to 6.74 Euro/MWh. However increasing both the wind and the solar to 2050 level actually gives lower bottleneck costs than increasing only the wind. This might be because the annual and diurnal pattern of the wind and solar production are very different from each other and the solar power might be producing at times when the wind power is low and vice versa. This could cause the highest peaks and bottoms of production to be levelled out, giving less strain on the grid. This shows that having different kinds of renewable power with different production patterns can be beneficial for the grid costs.

Effect of wind on costs

Next the effect the wind has on the bottleneck costs are analysed, by looking at the costs both with wind in the system and with the wind set to zero, this will show how the wind influence the cost of the grid restrictions. An analysis is also made of how the variability of wind affects the bottleneck costs.

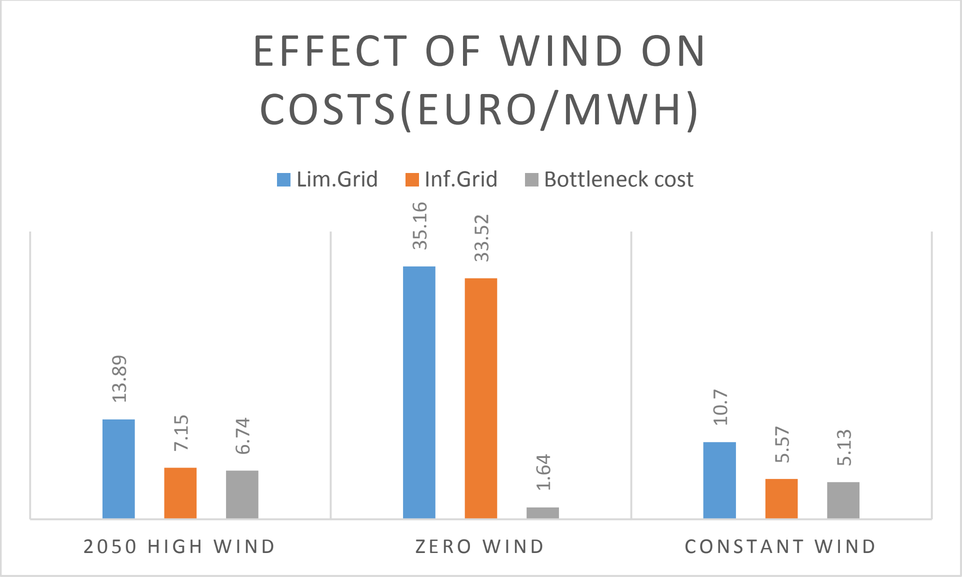


Figure 55, Costs, 2050 Wind, Zero Wind and Constant Wind

The diagram shows that the costs both with limited and infinite grid would be much higher with zero wind compared to 2050 wind, but that the wind puts a strain on the grid and that the bottleneck costs will be 5.1 Euro/MWh higher with 2050 wind than with zero wind. In the 2030 base scenario the wind decreased the bottleneck costs with 0.93 Euro/MWh. This shows that when the wind becomes this high it contributes to making the grid more congested as opposed to the 2030 level of wind, when the wind contributed to making the grid less congested. Referring to the maps showing the AC congestions and the HVDC flows both in 2030 and with 2050 wind this can be explained. In 2030 the wind helps to supply the load in areas with high demand such as Germany and France, and these countries need less import than they would without the wind. In the 2050 wind scenario countries with a high amount of wind and solar such as Germany and France have more than enough to supply their own load for many of the hours and the wind and solar power needs to be transported out of these countries.

The bottleneck cost with constant wind is 5.13 Euro/MWh, as opposed to 6.74 Euro/MWh with variable wind. This means that the variability of wind increases the bottleneck costs with 1.61 Euro/MWh. In the 2030 base scenario the variability of wind only increased the bottleneck costs with 0.29 Euro/MWh. The costs of the variability of wind is higher in the 2050 wind scenario which might further improve the profitability of different storage options. This is left for further studies.

Effect of solar on costs

The figure below shows the bottleneck costs for the 2050 solar scenario. To study the effect of the solar and the variability of solar on bottleneck costs the costs with zero solar and constant solar are also shown.

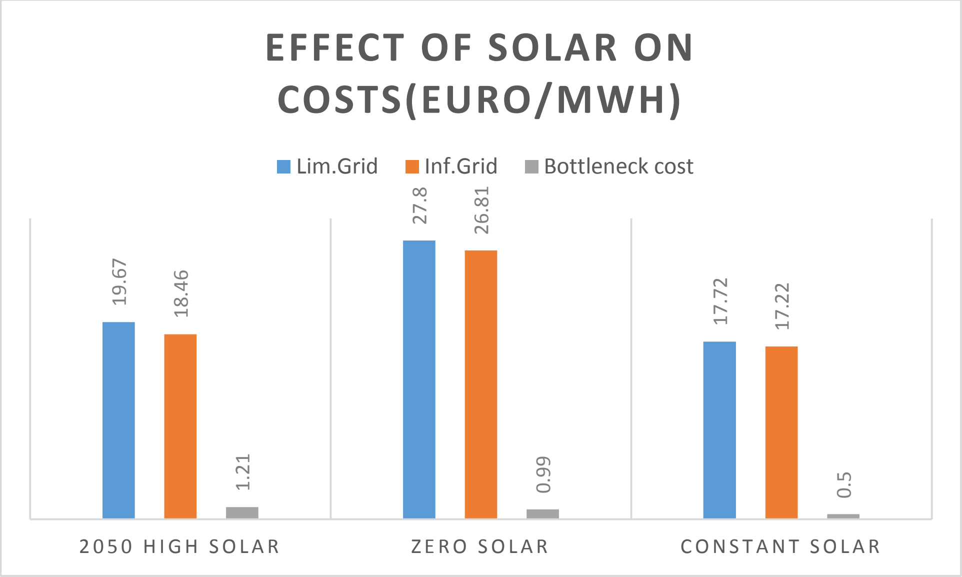


Figure 56, Costs, 2050 Solar, Zero Solar and Constant Solar

The bottleneck costs with 2050 solar is 1.21 Euro/MWh, without any solar the bottleneck costs are 0.99 Euro/MWh. This means that the 2050 solar increase the bottleneck costs with 0.22 Euro/MWh. The wind increased the bottleneck costs with 5.1 Euro/MWh. This means that increasing the wind power to 2050 level puts a much higher strain on the grid than increasing the solar power to 2050 level. This is partly because the installed solar capacity in 2050 solar is 603 GW, while the wind capacity in the 2050 wind scenario is 1024 GW, but it is also because the utilisation time of the solar is much lower, meaning that less will be produced and that the grid will be affected less. In the 2030 base scenario the solar production decreased the bottleneck costs with 0.28 Euro/MWh. This shows that also for solar power the effect it has on the grid is positive at 2030 level, but becomes negative when it is increased to 2050 level.

The variability of solar power increased the bottleneck costs with 0.71 Euro/MWh for the 2050 solar scenario. This shows that for solar power it is the variability that is to blame for the highest share of the bottleneck costs. This might be because many of the countries have a low load during the time when the solar radiation is at its highest. This might give too much production compared to load in some of the areas with a high amount of solar and therefore a high incentive to export power. In the 2030 base scenario the variability of the solar power increased the bottleneck costs with 0.1 Euro/MWh, this shows that the variability of solar influence the grid more with the 2050 amount of solar power. Meaning that also the variability of solar could make new storage alternatives profitable when the capacity is increased to 2050 level.

Effect of Solar and Wind on costs

In the diagram that follows the effect on the average costs of wind and solar power are investigated. The costs are shown for the 2050 wind and solar scenario. The costs are also shown with both the wind and solar set to zero and with both the wind and solar set to a constant value.

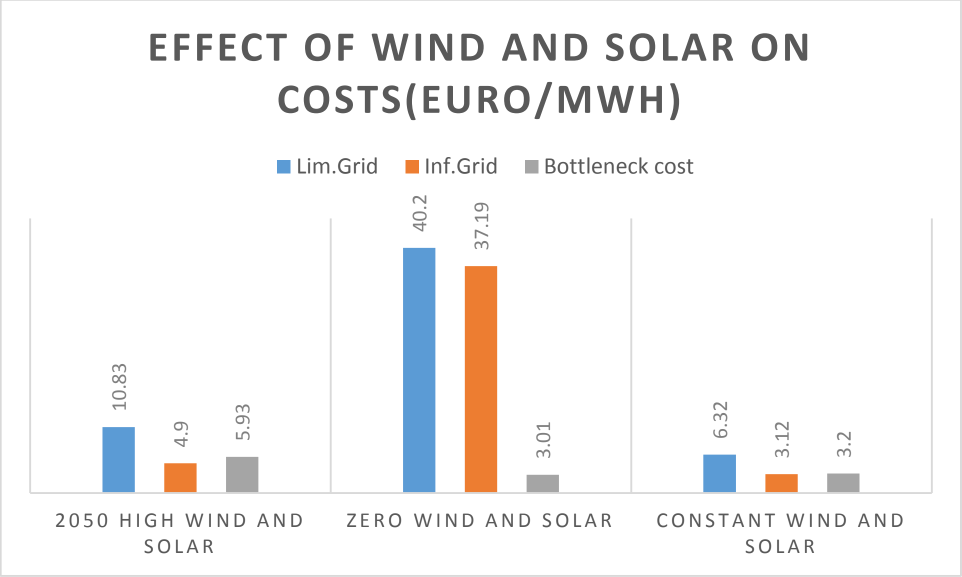


Figure 57, Costs 2050 Wind and solar, Zero Wind and Solar and Constant Wind and Solar

The figure shows that wind and solar reduce the average costs with a very high amount. The cost reduction with 2050 wind and solar compared to zero wind and solar is 29.37 Euro/MWh. This is because removing the wind and solar power would lead to more expensive production from thermal plants.

The bottleneck costs with wind and solar combined are 5.93 Euro/MWh, which is higher than the 2050 solar scenario, but lower than the 2050 wind scenario. The bottleneck costs with zero wind and solar are 3.01 Euro/MWh, showing that the wind and solar combined contributes to increasing the bottleneck costs with 2.92 Euro/MWh. In the 2030 scenario the wind and solar combined lowered the bottleneck costs with 2.3 Euro/MWh.

In the 2050 wind scenario the wind alone increased the bottleneck costs with 5.1 Euro/MWh, while the increase in bottleneck costs from wind and solar combined are 2.92 Euro/MWh. The reason for this must be that the combined increase of wind and solar is more beneficial when it comes to grid costs than only increasing the wind power. This must be because the wind and solar production patterns level each other out so that it fits the load profile better.

Making both the wind and solar constant gives lower bottleneck costs than with variable wind and solar. The bottleneck costs is also lower than it was with the 2050 wind scenario and constant wind. This is probably because the 2050 wind scenario with constant wind still had variable solar at 2030 level.

4.2.9 Effect of congestions on prices

This section studies the influence the grid has on the prices. First the prices are found with infinite grid, then with limited grid. The diagram below shows the difference in price with infinite and limited grid. This is shown for the 2050 wind, 2050 solar and the 2050 wind and solar scenario.

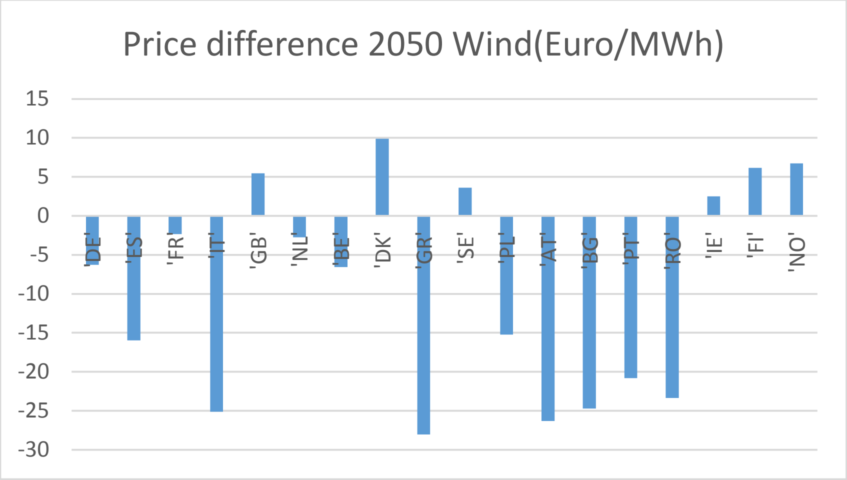


Figure 58, 2050 Wind Price(Inf grid)-2050 Wind Price(Lim grid)

The figure shows that the countries that experience a price increase when the grid capacity is changed to infinity are Great Britain, Denmark, Sweden, Ireland, Finland and Norway. These countries also experienced a price increase with infinite grid in the 2030 base scenario. In addition, the Netherlands had a price increase with infinite grid in the 2030 base scenario. The mean price in the system with infinite grid was 21.75 Euro/MWh. The six countries with the lowest mean price are those that get a price increase if the grid were infinite. In the 2030 base scenario the price difference for the Nordic countries were a lot higher than in the 2050 wind scenario. In the 2030 base scenario the price in the Nordic countries increased with between 15 and 20 Euro/MWh. While in the 2050 wind scenario the price increase is below 10 Euro/MWh for all the Nordic countries, and Great Britain actually has a higher price increase than Sweden. The utilisation of wind was strongly influenced by the grid as shown in Figure 32. All the countries with a price increase experienced a strong reduction in the utilisation of wind with limited grid compared to infinite grid. Denmark, Netherlands and Great Britain were the countries that experienced the strongest increase in utilisation of wind when the grid was set to infinite. This is probably what contributes the most to the price increase in Great Britain and Denmark. The Norwegian and Swedish hydro power are a part of the explanation for the price increase in the Nordic countries. When the grid is infinite the Nordic countries will no longer benefit alone from the high availability of cheap storable hydro power, this advantage will to a much higher extent be shared with the countries that have connections to the Nordic countries such as Germany, Netherlands and Great Britain.

For the countries were the prices decrease with infinite grid, there is a higher price reduction with 2050 wind than it was with 2030 wind. In the 2030 scenario all countries apart from Portugal had a price decrease that was lower than 10 Euro/MWh. This means that the grid contributes to increasing the prices more with 2050 wind than with 2030 wind. This is logical since the increased wind power need more transmission capacity to be transported to the areas with the highest prices. This means that there is a higher benefit of having an infinite grid with 2050 wind compared to 2030 wind when it comes to lowering the prices.

Next the price difference with infinite and limited grid are analysed for the 2050 solar scenario.

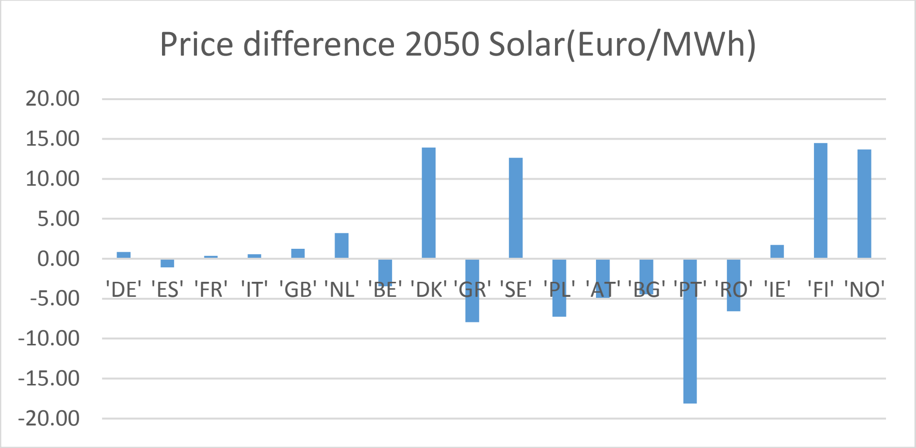


Figure 59,2050 Solar Price(Inf grid)-2050 Solar Price(Lim grid)

Compared to the 2030 base scenario the price increase in the Nordic countries are substantially lower for the 2050 solar scenario, for example Norway had a price increase of 18.4 Euro/MWh in the 2030 base scenario, in the 2050 solar scenario this is only 13.7 Euro/MWh. The installed solar power in the Nordic countires is very low. The reason why the price increase with infinite grid is lower with 2050 solar than with the 2030 base scenario is that the continental countries have a high increase in solar power. The need for import from the Nordic countries is therefore reduced and the increased transmission capacity from the Nordic countries is less important.

Germany, France and Italy had a price reduction with infinite grid in the 2030 base scenario, but with the 2050 solar scenario the prices slightly increase with infinite grid. These are also the countries with the highest amount of solar power. This makes it natural that these countries experience a price increase when the grid is infinite because they can no longer benefit from the increased solar power alone.

The figure below shows the price difference with the 2050 wind and solar scenario.

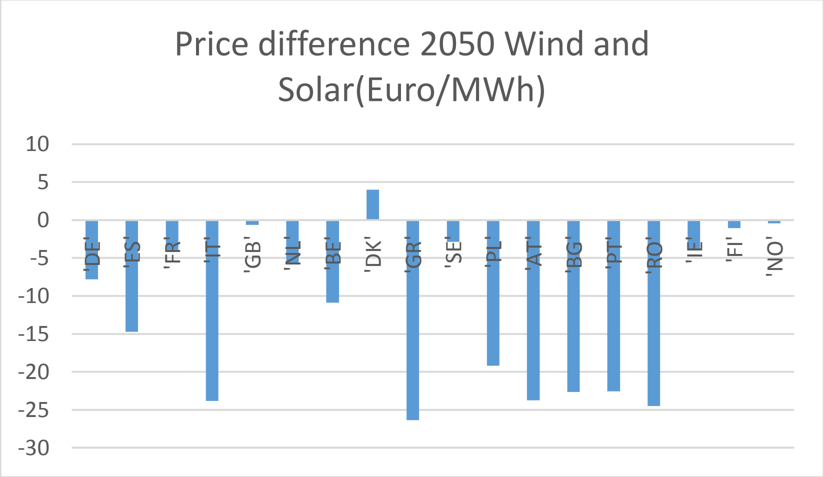


Figure 60,2050 Wind and Solar Price(Inf grid)-2050 Wind and Solar Price(Lim grid)

In the 2050 wind and solar scenario the price decrease with infinite grid for all the countries apart from Denmark. This means that all the countries benefit from making the grid infinite except for Denmark. Denmark is the country with the lowest price of all countries in the 2050 wind and solar scenario, hence all the other countries wants to buy from Denmark and the price increase there. The reason why so many of the countries have a price decrease with infinite grid is that the wind and solar production sometimes is so high that the price becomes zero. Due to the variability of wind and solar this can happen at different times on each side of a transmission line. Removing the limitations of the line might therefore lead to a decrease in mean price on both sides of the transmission line.

4.3 2050 Whole Scenario

The generation capacities are adapted to the 2050 high scenario from the Energy roadmap [2]. Section 4.3.1 gives an overview of how much each generation type is changed compared to 2030 level.

4.3.1 Changes to generation mix

Coal:

Both the installed lignite coal and hard coal are reduced with about 40 % compared to 2030 level from a total installed capacity of 118.5 GW to 70 GW.

Oil:

The amount of installed oil capacity is also reduced with about 40 % from a total capacity of 43.3 GW to 25.7 GW.

Gas:

The amount of installed gas capacity is reduced with about 30 % from 286 GW to 200 GW.

Renewable other than wind(Biomass):

The 2050 scenario has a high increase in biomass powered plants compared to the 2030 scenario. This leads to an increase in the installed capacity of renewable other than wind of about 3 times the 2030 level, from 54.4 GW to 167 GW.

Nuclear:

The highest decrease in installed capacity is for nuclear power plants, since the 2050 high RES scenario assumes large consequences on public attitude towards nuclear power as a consequence of the Fukushima accident. The installed nuclear power is reduced with about 60 % from 105 GW to 41.45 GW. The highest consequence of the reduction in nuclear power is found in France which has the highest amount of nuclear power in 2030. France experience a reduction of installed nuclear power from 40 GW in 2030 to 15.6 GW in 2050.

4.3.2 Wind Power Production

The wind power production with limited and infinite grid is shown in the table below together with the wind utilisation times.

2050 Whole Scenario	Total Wind Prod(TWh)	Wind utilisation time(h)
Limited grid	1864.61	1819.24
Infinite grid	2451.36	2391.71

Table 27 Wind power production and utilisation time, limited and infinite grid

The total wind power production with the 2050 Whole scenario is 1864.6 TWh, with a total installed capacity of 1024.9 GW this gives a utilisation time of 1819.2hours. For the scenario where only the wind and solar were changed the total production was 1860.6 TWh. This means that the wind power production has increased with 4 TWh in the whole scenario compared to the scenario with increased wind and solar power. This increase in wind power production must be caused by the reduction in nuclear power. Nuclear power has a higher marginal cost than wind power, but cannot be regulated as easily as other energy sources. Nuclear is set internally in PSST so that it has a minimum production that is 20% of the installed capacity. In a situation with high enough production from energy sources with zero marginal cost to fulfil the entire load within an area, the nuclear power will be turned to its minimum level. This minimum level is higher in the 2050 wind and solar scenario than in the 2050 whole scenario. In the 2050 whole scenario less wind power has to be turned off to create balance between supply and demand compared to the 2050 wind and solar scenario. This gives a slightly higher wind production in the 2050 whole scenario.

The table also shows that the production and utilisation times with infinite grid has increased substantially. This is natural since the grid restrictions will no longer prevent the wind power from being transferred to the surrounding countries. In the 2050 wind and solar scenario the utilisation time with infinite grid was 2380.6 hours, which means that the utilisation time with infinite grid is about eleven hours higher for the whole scenario as a consequence of the change in the installed capacity mix. The total production for the 2050 whole scenario with infinite grid is 31.47% higher than with limited grid, for comparison the grid only limited the production of wind with 1.29 % in the 2030 base scenario.

The duration curve for the wind power production for the 2050 whole scenario is shown below together with the duration curve for the 203 base scenario.

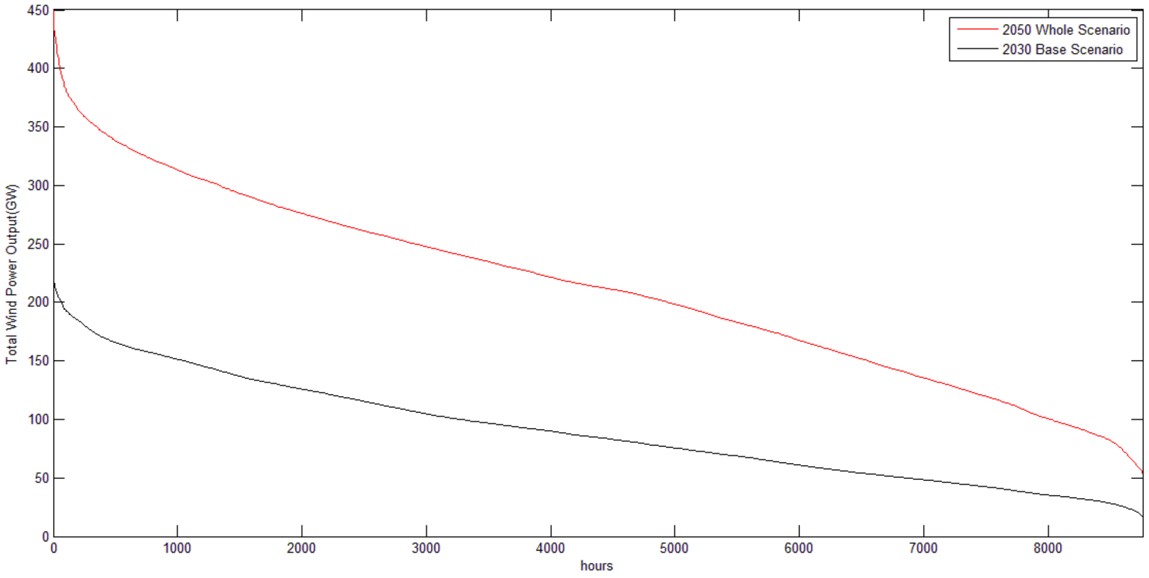


Figure 61, Wind duration curve 2050 whole and 2030 base

The duration curve shows that for the 2050 whole scenario the curve is steeper at the highest capacities than for the 2030 curve. The maximum total wind output in the 2050 whole scenario is 449.2 GW, which is 43.83% of the installed capacitiy. In the 2030 base scenario the maximum wind power output was 66.75% of the installed capacity, showing that less of the wind power can be exploited with this high amount of installed capacity. The minimum total wind power output is 53.09 GW, which is 5.18 % of the installed capacity. In the 2030 base scenario the minimum wind power output was 5.02% of the installed capacity. The mean production for the 2050 whole scenario is 212.9GW, which is 20.77 % of the installed capacity. In the 2030 base scenario the mean production was 26.2% of the installed capacity. The reason why both the maximum and the mean production are lower for the 2050 whole scenario than the 2030 base scenario might be that the grid become congested as a consequence of the high wind production or it might be that the load is covered and the wind power are turned off for some hours.

The utilisation time for the countries with the highest amount of renewable energy are shown below.

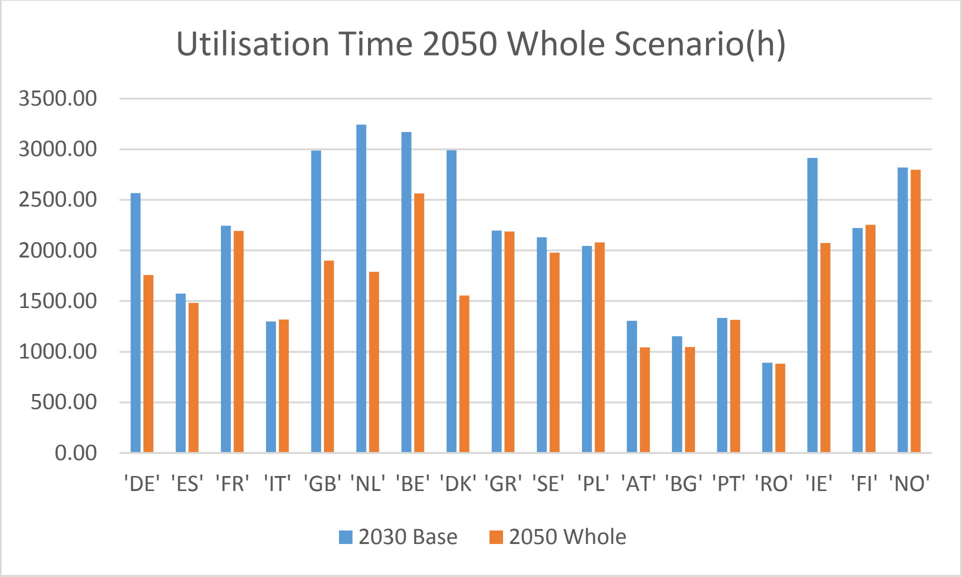


Figure 62, Wind power utilisation time 2050 Whole and 2030 base

There is a high variation between the countries how much the utilisation is changed between the 2030 scenario and the 2050 whole scenario. It is Germany, Great Britain, Netherlands , Belgium, Denmark and Ireland that has the highest decrease in utilisation time. In Norway there is only a very small reduction in utilisation time, this is caused by the three offshore wind farms that are added outside the coast of Norway that have a high utilisation time and will contribute to increase the utilisation time in Norway. The reduction in utilisation for many of the countries can be explained by the limitations in the grid that might occur when the installed wind power capacity is increased. The difference in the utilisation of wind power when the grid is infinite and limited is shown in the diagram below.

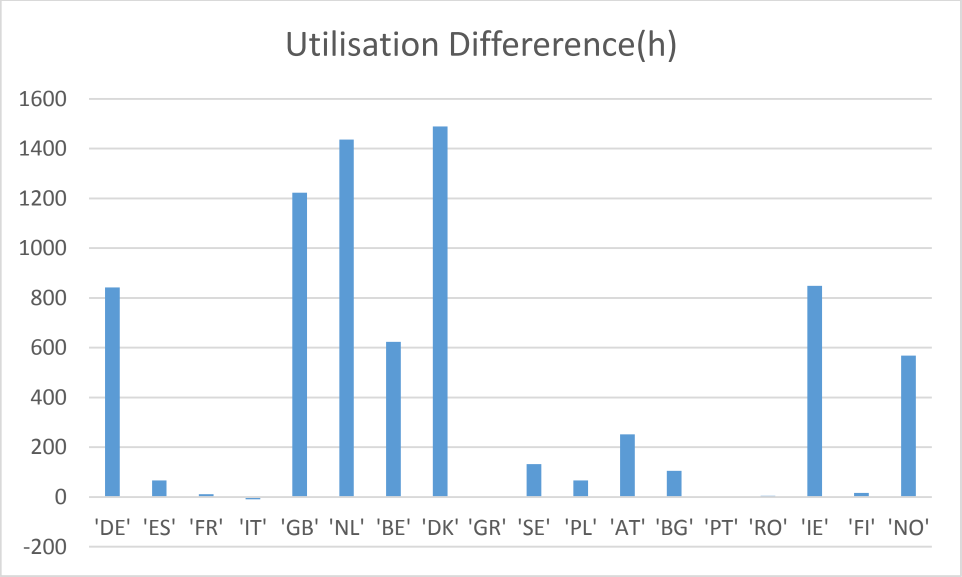


Figure 63 Wind utilisation(Inf grid)-Wind utilisation(Lim grid)

Figure 63 shows that the utilisation reduction caused by the grid is much higher than it was in the 2030 base scenario, where the highest utilisation difference was for Great Britain and was around 180 hours. Norway has a small reduction in utilisation time compared to the 2030 base scenario, but has a significant reduction in wind utilisation as a consequence of the grid. In the 2030 base scenario Norway had no reduction in wind utilisation as a consequence of the grid, therefore it would have been natural that the utilisation in the 2050 whole scenario was significantly lower than in the 2030 base scenario. This is not the case because of the three new offshore wind farms in Norway that contributes to increasing the wind power utilisation.

The countries who had a reduction of utilisation time in the 2030 base scenario are those with the highest reduction in the 2050 whole scenario, that is Germany, Great Britain, Netherlands, Denmark and Ireland.

4.3.3 Solar production

Next the solar production for the 2050 whole scenario is considered. The total installed solar capacity is 603 GW. The table below shows the total amount of solar production and the total duration time.

2050 Whole Scenario	Total Solar Prod(TWh)	Solar utilisation time(h)
Limited grid	596.11	988.58
Infinite grid	572.15	948.83

Table 28 Total solar production and utilisation time 2050 Whole Scenario

The total solar production for the 2050 whole scenario is 596.11 TWh. The total solar production was 584.03 TWh in the 2050 wind and solar scenario. This means that also for solar power, reducing the nuclear capacity increases the production. The table shows that the utilisation time is lower with infinite grid than with finite grid, indicating that with infinite grid the solar power are turned off at some hours because the load is supplied. This was discussed in detail under the chapter about 2050 wind and solar. To make sure that the results are logical the combined production from both wind and solar with infinite and limited grid are shown in the table below

Installed Wind and Solar Cap(GW)	1627.9
Annual Production Lim. grid(TWh)	2460.72
Annual production Inf grid(TWh)	3023.51

Table 29 Installed Wind and solar cap and combined wind and solar production 2050 Whole

Table 29 shows that the total annual production of wind and solar is higher for the infinite grid case. Which proves that the total utilisation of the installed capacity with zero marginal cost is still higher with infinite grid than with limited grid.

The duration curve for the solar production for the 2050 whole scenario is shown below.

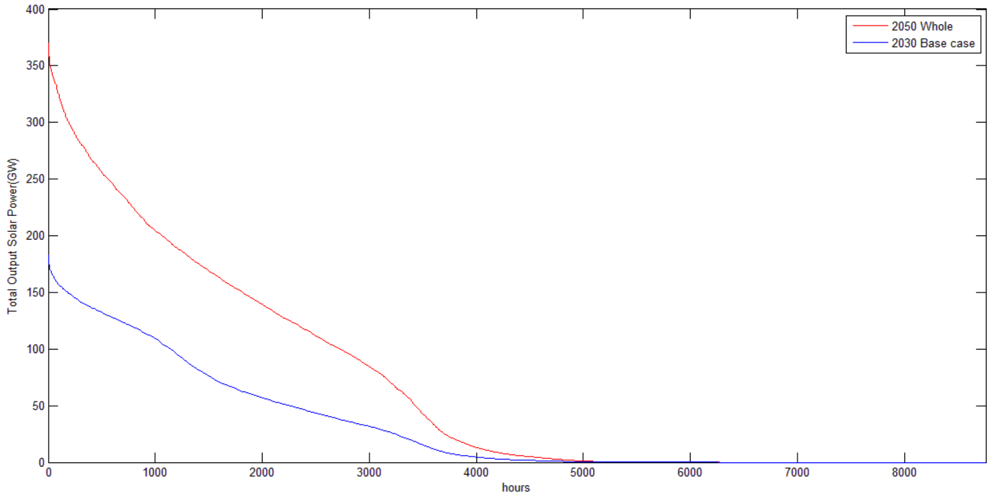


Figure 64, Solar duration curve, 2050 whole and 2030 base

The maximum total solar output is 369.6GW, which is 61.3% of the installed capacity. In the 2030 base scenario the maximum production was 90.61% of the installed capacity. It is as expected that less of the solar can be utilized when both the wind and solar production are increased. The mean production is 68.05 GW, that is 11.3% of the installed capacity. In the 2030 base scenario the mean production was 15.59 % of the installed capacity.

Next the utilisation of solar for the countries with more than 3 GW of installed solar power are shown for the 2050 whole scenario together with the 2030 base scenario.

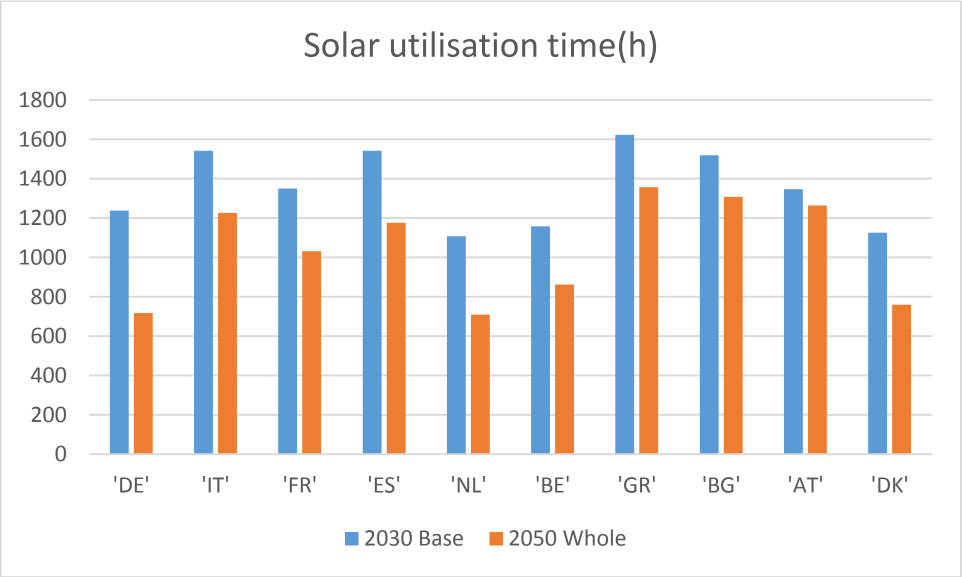


Figure 65, Solar utilisation time, 2050 Whole and 2030 Base

The solar utilisation diagram shows that Germany is the country with the highest reduction in utilisation time compared to the 2030 base scenario. After this comes Netherlands, Spain and Denmark. Germany is the country with the highest amount of both solar and wind, so it is expected that the grid will limit the production here and also that the production might become so high that the load is fulfilled for some hours.

Next follows a table that shows the utilisation difference between the infinite grid and limited grid case.

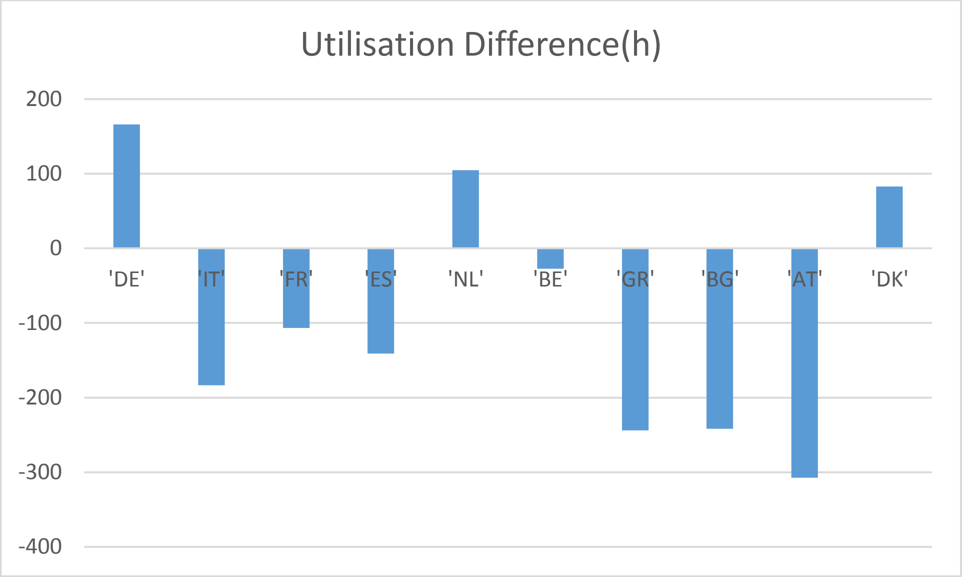


Figure 66, Whole scenario, Solar Utilisation(Inf grid)-Solar utilisation(Lim grid)

For several of the countries with the most solar the solar utilisation decrease when the grid is infinite. As mentioned above this is linked to the fact that the solar power is turned off sometimes with infinite grid because the load is supplied. The utilisation does not decrease in Germany that is the country with the highest amount of solar power. That means that for Germany it is the grid limitations surrounding the country that to a large extent limit the production.

4.3.4 Fossil production

In the 2050 whole scenario the total fossil fuel generation capacity has decreased to 293.3 GW. In the 2030 scenario and all the previous scenarios the total fossil fuel capacity was 442.4 GW.

2050 Whole Scenario	Total Fossil Production(TWh)	Fossil utilisation time(h)
Limited grid	450.03	1534.40
Infinite grid	74.81	255.07

Table 30 Fossil power production and utilisation time, limited and infinite grid

The total production from fossil fuels in the 2050 whole scenario is 450.025 TWh. In the 2030 base scenario this production was 1393.35 TWh. In the 2050 wind and solar scenario the total production was 489.93 TWh. The fact that the fossil production is lower in the 2050 whole scenario than the 2050 wind and solar scenario means that reducing the fossil capacity and increasing the biomass capacity helps to reduce the total fossil production. The fossil production is much lower with infinite grid than with limited grid, proving that removing some of the bottlenecks between countries lead to better utilization of renewables and thus less need for production from fossil plants.

The duration curve for the 2050 whole scenario together with the duration curve for the 2030 base scenario is shown in the figure below.

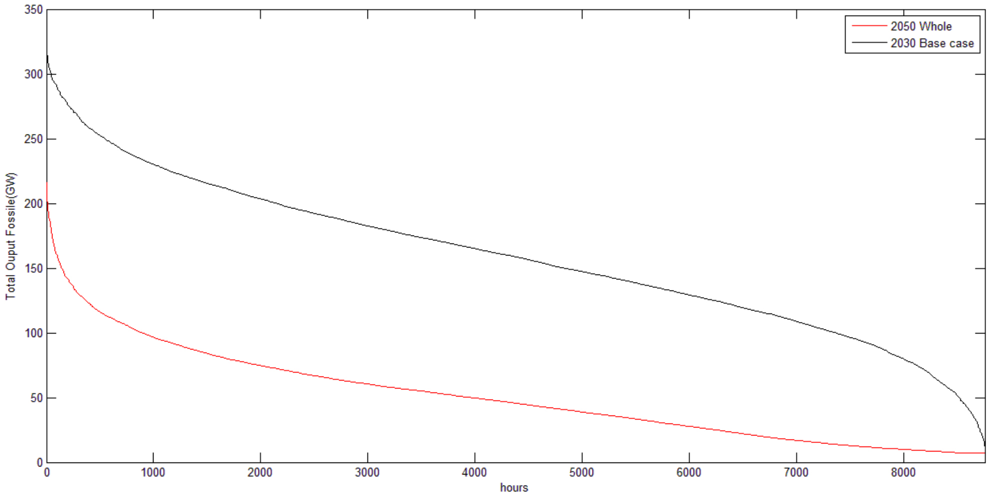


Figure 67 Duration curves for 2050 whole scenario and 2030 base scenario

The duration curve of the fossil production for the 2050 whole scenario has a different shape compared to the duration curve for the 2030 base scenario. The 2030 base scenario curve falls slower than the 2050 whole scenario curve for most of the hours, but falls suddenly to a lower level towards the lowest production level. The maximum fossil output in the 2050 whole scenario was 215.8 GW, which is 73.6% of the installed capacity. In the 2030 base scenario the maximum production was 72.67% of the installed capacity. Due to the decrease in installed fossil capacity the maximum capacity is about the same percentage of the installed capacity for both scenarios. In the 2050 wind and solar scenario the amount of installed fossil power was higher and the maximum output was 244.1GW, which is higher than in the 2050 whole scenario, showing that at the hours when the most fossil power is needed the production is lower because of the reduction in installed capacity. The mean production in the 2050 whole scenario is 55.93GW, which is 12.6% of the installed capacity.

The diagram below shows the fossil utilisation time for the 2050 whole scenario together with the utilisation times for the 2030 base scenario and the 2050 wind and solar scenario.

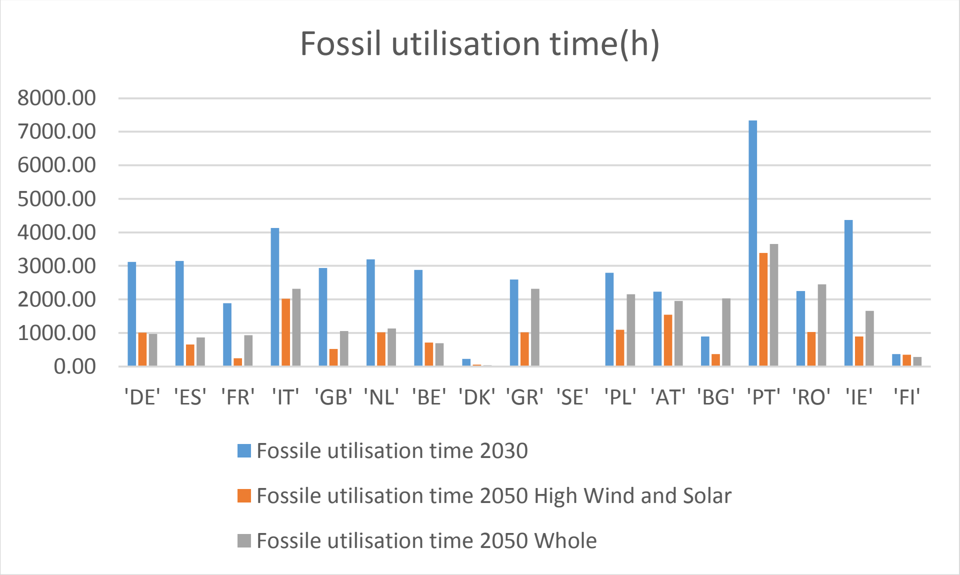


Figure 68 Fossil utilisation time in 2050 whole, 2050 wind and solar and 2030 base scenario

The diagram shows that the utilisation time has decreased a lot for most countries compared to the 2030 base scenario. For Bulgaria and Romania the utilisation time has increased compared to the 2030 base scenario. For most countries the utilisation of fossil in the 2050 whole scenario is higher than the 2050 Wind and Solar scenario. This is natural since the capacity is about half compared to the 2050 wind and solar scenario. Even though the utilisation time has increased the production is still lower for the 2050 whole scenario than the 2050 wind and solar scenario. The diagram shows that Sweden never use any of its installed fossil power and Denmark only use fossil power in the 2030 base scenario.

4.3.5 Prices

The mean prices for the 2050 whole scenario is shown below together with the mean prices for the 2030 base scenario and the 2050 wind and solar scenario.

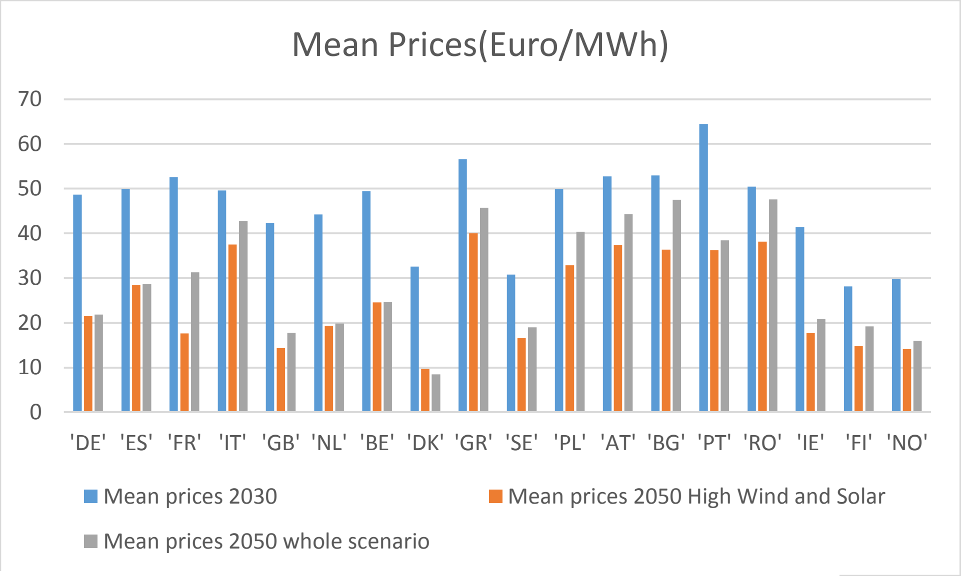


Figure 69 Mean prices 2050 whole, 2050 wind and solar and 2030 base scenario

The 2030 base scenario has the highest price for all the countries which is natural since there is less installed wind and solar in this scenario. For most of the countries the mean price is higher for the 2050 whole scenario than the 2050 wind and solar scenario. Denmark is the only country where the mean price for the 2050 wind and solar scenario is higher than the mean price for the whole scenario. The reason why the mean price for most countries is higher with the 2050 whole scenario is that the production capacity is lower in this scenario, since both the nuclear power and the fossil power is reduced, and the reduction of these sources are about twice the increase in biomass powered plants. Especially the reduction of nuclear power will lead to an increase in mean price for the 2050 whole scenario compared to the 2050 wind and solar scenario. It is difficult to say exactly why Denmark has a higher price in 2050 wind and solar scenario, but part of the explanation could be that Denmark had no fossil production in either of the two scenarios and no installed nuclear power, so these changes will not influence the prices as much. In addition Denmark has 4.16 GW of biomass installed in 2030 which is increased with about 3 times in the 2050 whole scenario.

4.3.6 Production mix in Europe in the 2050 whole scenario

The diagram below shows the share of the total production for each generation type for the 2050 whole scenario.

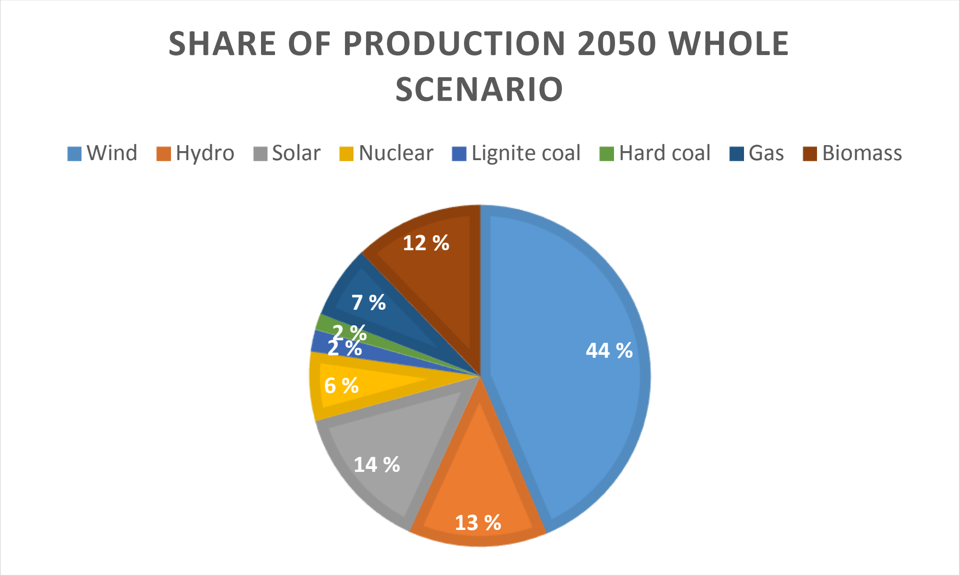


Figure 70 Production mix in the 2050 whole scenario

The figure shows that the wind power now has the highest share of the total production, with a total share of 44%. The results of the simulations performed in the Energy Road map showed that the wind constituted 48.7% of the total production [2], so the wind share found with PSST is not that different, but 4.7% lower.

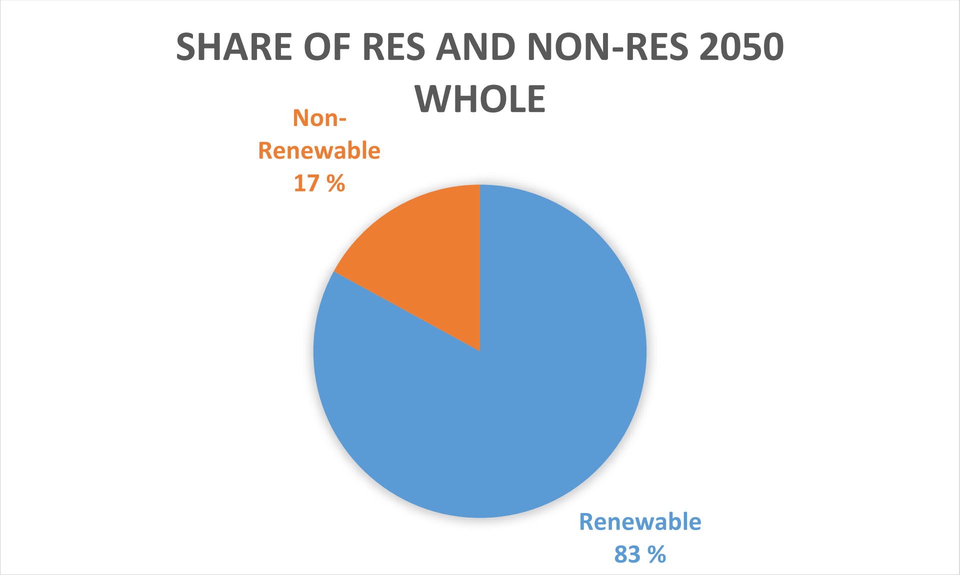


Figure 71 Renewable and non-renewable power production in 2050 whole scenario

The overall share of Renewable production, including wind, hydro, solar and biomass is 83%. The results of the simulations performed in the Energy Roadmap 2050 showed that 83.1% of the production was from RES in the high RES scenario [2], which is very consistent with the PSST results. The share of hydro production of the total production has decreased from 14% in the 2030 base scenario to 13% in the 2050 whole scenario. It is the high increase in wind and solar that causes the highest increase of the RES share. This means that of the total RES power a much lower share is storable hydro power than in the 2030 base scenario. This gives many challenges when it comes to balancing and storage.

The chapters about wind and solar production showed that the wind and solar utilisation strongly decreased when the capacities were increased to 2050 level. An important question that rises from this is how much it is profitable to increase the wind and solar power. An economic analysis of this is out of the scope of this thesis. However a small discussion of how much RES that should be installed is given in this section. The figure below shows the load together with the total RES production from wind, solar, hydro and biomass for the 2050 whole scenario. It was shown earlier in this section that the utilisation of wind and solar power were reduced due to grid limitations and potential RES being higher than the load for some hours. The figure also shows the duration curve of the RES capacity that should be installed if the production should be guaranteed to never exceed the load. In addition it shows the duration curve of the RES capacity that should be installed to guarantee that all load at all times are covered by RES.

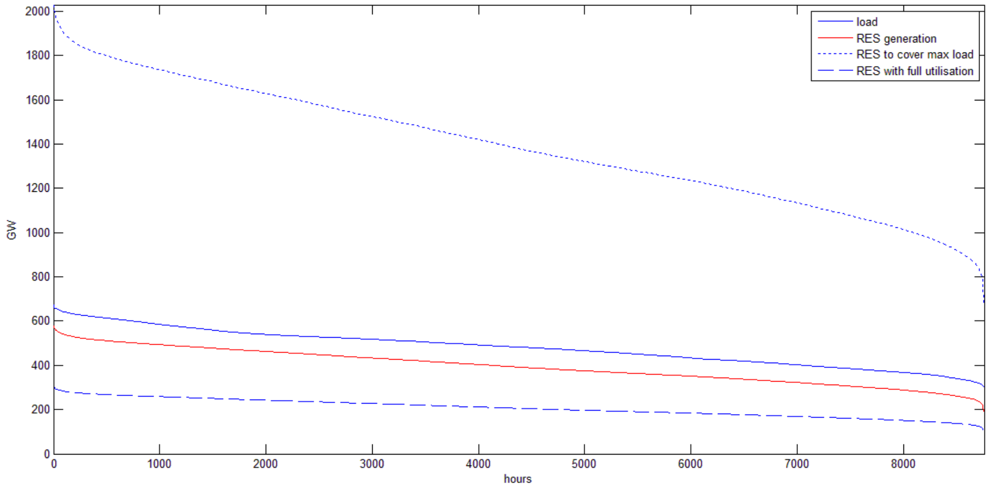


Figure 72 Load and RES generation in the 2050 whole scenario, RES needed to cover max load and RES that would give full utilisation

If there should be enough RES installed to guarantee that the max load is covered, the minimum production of RES would have to be equal to the maximum load. This would give a very high reduction of the utilisation of RES and very high investment cost. It is very unlikely that this could be profitable. If there should be no risk of reduction in utilisation time due to the RES potential exceeding the load the production of RES should never be higher than the minimum load. It should be noticed that there could still be reduction in utilisation due to grid limitations. The curves showing the RES to cover max load and the RES with full utilisation is found by scaling the existing RES production duration curve for the 2050 whole scenario. The scaling factor giving the RES to cover maximum load is found by dividing the maximum load by the minimum RES. The scaling factor giving the RES with full utilisation is found by dividing the minimum load by the maximum RES. The total installed capacity of RES in the 2050 whole scenario is 2034.1 GW, the installed RES that would be required to guarantee that the RES could cover the max load is 7158.12 GW, the RES that should be installed to guarantee that the RES utilisation is never limited by the RES potential exceeding the load is 1066.45 GW. The total installed capacity in the 2030 base scenario was 840.6 GW. The RES capacity that would give full utilisation when not regarding grid limitations is in other words still higher than the RES capacity in the 2030 base scenario. Some conclusion about the profitability of new RES can be drawn from Figure 72. First, it is clear that it would be meaningless to install more RES than suggested by the RES to cover max load curve, because this RES production will always fulfil the load. Secondly an installed RES that gives a production curve that is at the same level or above the load curve would be able to supply the sufficient energy over the course of one year and would be able to fulfil the load if there always were enough storage.

4.3.7 Exchange

The table below shows the utilisation of HVDC lines for the 2050 whole scenario, and the figure shows the map of the main HVDC flows.

		Capacity	Utilisation(%)		
From	To		Total	From-To	To-From
NO	GB	1400	95.39	45.80	49.59
NL	NO	1400	96.78	3.29	93.50
DE	NO	1200	92.49	15.57	76.92
NO	DK	1700	67.52	17.23	50.29
NL	GB	1290	95.30	74.45	20.85
BE	GB	9500	48.36	27.74	20.62
FR	GB	5000	90.01	24.11	65.89
SE	PL	2890.8	75.83	75.18	0.65
SE	LV	1000	87.79	70.01	17.78
FI	EE	2000	71.08	63.26	7.82
FR	IE	1000	93.44	32.98	60.46
GB	IE	1460	60.68	25.71	34.97
DE	SE	2678.5	73.82	40.17	33.65
West DK	NL	700	99.03	96.36	2.67
East DK	DE	550	93.28	53.93	39.35
East NO	SE	1100	66.12	50.71	15.41
SE	DK	485	96.43	14.26	82.16
SE	FI	2350	70.89	64.70	6.18

Table 31 HVDC utilisation 2050 Whole scenario

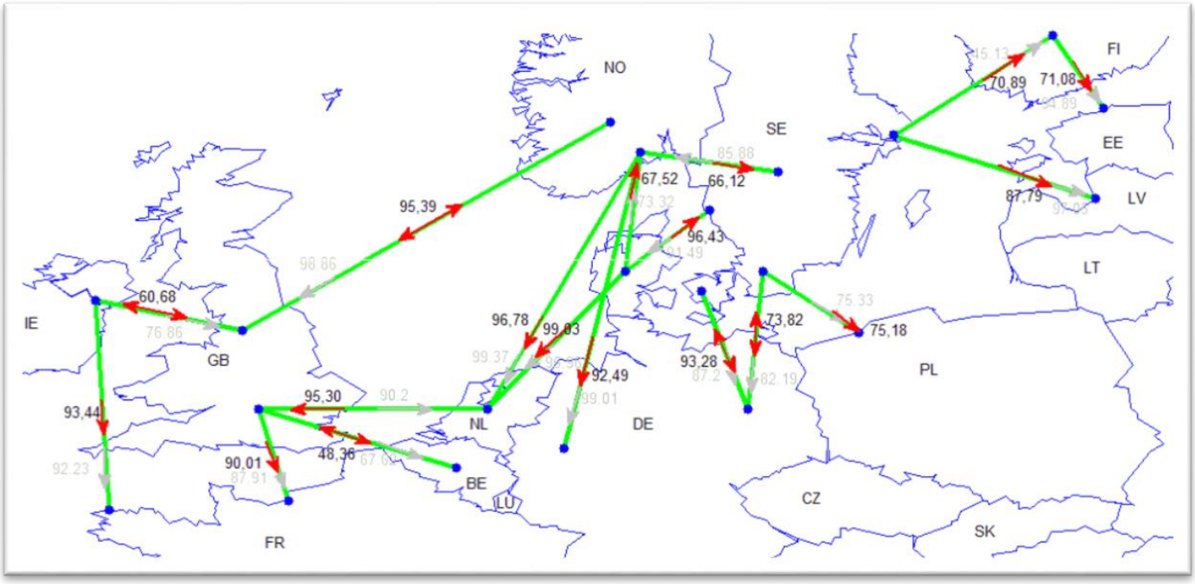


Figure 73 HVDC utilisation 2050 Whole scenario

The flow between Norway and Great Britain has become bidirectional compared to the 2030 base scenario when almost all the flow was from Norway to Great Britain. The overall utilisation of the cable has decreased a bit, but not with a substantial amount. Compared to the 2050 wind and solar scenario a higher percentage of the flow goes from Norway to Great Britain. This is most likely because Great Britain has a substantial amount of nuclear and fossil fuel installed which are reduced in the 2050 whole scenario. More power from Norway might therefore be needed in times when the wind power production is low.

When it comes to the flow from Norway to Netherlands and Germany, the flow was almost entirely from Norway in the 2030 base scenario and both cables were close to fully utilized. For both these cables the utilisation has decreased with a few percentage points. The utilisation from Netherlands to Norway and From Germany to Norway has increased, while the utilisation on these cables in the direction from Norway has decreased. This is due to the strong increase in wind and solar power on the continent and are very similar to the results seen under the 2050 wind and solar scenario.

The flow between Great Britain and France are more in the direction from France to Great Britain than in the 2030 Base scenario, probably due to the large amount of wind power on the continent. This is similar to the flow in the 2050 wind and solar scenario. Also the flow between Great Britain and Belgium are more from Belgium to Great Britain than in the 2030 base scenario, in fact the flow is bidirectional. This was the same in the 2050 wind and solar scenario. When it comes to the flow between Great Britain and the Netherlands this has changed direction in the 2050 whole scenario compared to the 2030 base scenario. The flow was 67.4 percent of the total utilisation from the Netherlands to Great Britain in the 2050 wind and solar scenario, while in the 2050 whole scenario, this has increased to 78.12 percent. This might be caused by the substantial decrease of nuclear and fossil power in Great Britain. The amount of fossil is much smaller in Netherlands and there is no nuclear there.

The flow between Denmark and Germany and Sweden and Germany become bidirectional in the 2050 whole scenario. The utilisation increases on the cable between Sweden and Germany compared to the 2050 wind and solar scenario, and less of the utilisation is from Germany to Sweden. Meaning that Germany exports less power to Sweden due to the changes in generation mix. This is not surprising since Germany has a lot more fossil power than Sweden. The utilisation of the cable between Denmark and Germany has increased a lot in the 2050 whole scenario compared to the 2030 base scenario. In 2030 base the utilisation was only 87.2 percent, this has increased to 93.28 percent in the 2050 whole scenario. In the 2050 wind and solar scenario the utilisation from Germany to Denmark was higher than in the 2050 whole scenario. Meaning that Germany exports less to Denmark, which is not surprising since Germany has a higher amount of fossil fuel than Denmark.

4.3.8 AC Congestions

Next the AC congestions are evaluated. The congestions in the 2030 base scenario are shown together with the congestions of the 2050 whole scenario. All the lines that were congested in 2030 are included and if there are other lines in addition that are congested in the 2050 whole scenario these are also included in the map below.

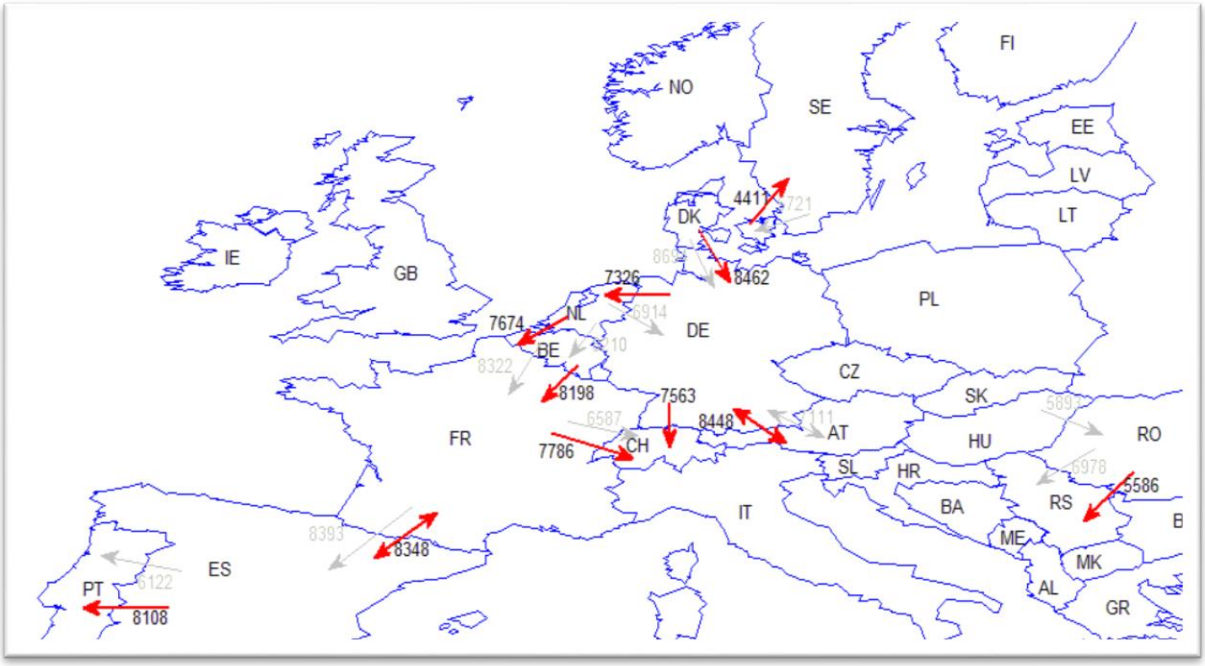


Figure 74 AC-congestions 2050 Whole and 2030 Base

The border between Germany and Switzerland was the only one that were among the most congested in the 2050 whole scenario that were not in the 2030 base scenario. No arrow is drawn between Hungary and Romania because there were zero hours of congestions across this border in the 2050 whole scenario.

The border between Denmark and Germany is still the most congested one. In the 2030 base scenario there was 8694 hours of congestion between Germany and Denmark. In the 2050 whole scenario this has decreased to 8462 hours. The percentage of hours that the congestions were from Denmark to Germany in 2030 was 99.25%, in the 2050 whole scenario this has decreased to 88.8 %. Meaning that more hours are congested from Germany to Denmark in the 2050 whole scenario compared to the 2030 base scenario. This is very similar to what was seen in the 2050 wind and solar scenario.

The congested hours between Denmark and Sweden has changed direction. In the 2030 base scenario there were 5721 hours of congestions, 99.25% of these being in the direction from Sweden to Denmark. In the 2050 whole scenario the hours of congestions have decreased to 4111 hours, and completely changed direction, now 95.2 percent of the congested hours are from Denmark to Sweden. In the 2050 wind and solar scenario the hours of congestions between Denmark and Sweden were only 3168 and the direction was bidirectional. The reason why more congestions are from Denmark to Sweden compared to the 2030 base scenario is that the general flow direction seems to have shifted from being only from the Nordic countries to the continent to becoming a mutual exchange. This is caused by the high amount of wind power. The reason why the flow goes more from Denmark to Sweden in the 2050 whole scenario compared to the 2050 wind and solar scenario is difficult to say, one explanation could be that Sweden has 10 GW of nuclear power in 2030 that are reduced in the 2050 whole scenario.

The congested hours between Germany and the Netherlands has changed direction. This was the same as was seen for the 2050 wind and solar scenario. The export from Germany to Netherlands has increased from 6675 GWh in 2030 to 30818 GWh in the 2050 whole scenario, a part of the reason for this is that Netherlands has increased its export to Great Britain from 3737 GWh in 2030 to 8412 GWh in 2050. In addition the Netherlands import less from both Norway and Denmark compared to the 2030 base scenario.

The border between Germany and Switzerland has become one of the most congested borders in the 2050 whole scenario. In the 2030 base scenario there was only 3860 hours of congestions across this border, with 89.6% being from Germany to Switzerland. In the 2050 whole scenario this has increased to 7563 hours with 85.02% being in the direction from Germany to Switzerland. The export from Germany to Switzerland has increased substantially from the 2030 base scenario to the 2050 whole scenario. In the 2030 base scenario the export was 12834.9 GWh, in the 2050 whole scenario this has increased to 18536.4 GWh. Switzerland has zero solar and a low amount of installed wind, and the prices there are high compared to most of the other European countries, therefore it is natural that the import goes up when the wind production increases in the surrounding countries.

There is no longer congestions between Hungary and Romania. The reason why the hours of congestions were strongly reduced also in the 2050 wind and solar scenario was that Romania has a lot more wind power than Hungary and the need for import becomes less. The reason why there are zero hours of congestions in the 2050 whole scenario, compared to 3251 hours in the 2050 wind and solar scenario is that Hungary and Romania are strongly influenced by the reduction of nuclear and fossil fuel powered plants.

4.3.9 Congestion costs

The congestion cost for the 2050 whole scenario is 6.71 Euro/MWh. For comparison the total congestion costs for the 2030 base scenario was only 0.71 Euro/MWh and for the 2050 wind and solar scenario it was 5.93 Euro/MWh. It is interesting that the bottleneck costs are higher with the 2050 whole scenario than with 2050 wind and solar scenario.

Influence of wind on congestion costs

The first that is analysed for the whole scenario is how the wind influence the congestion costs.

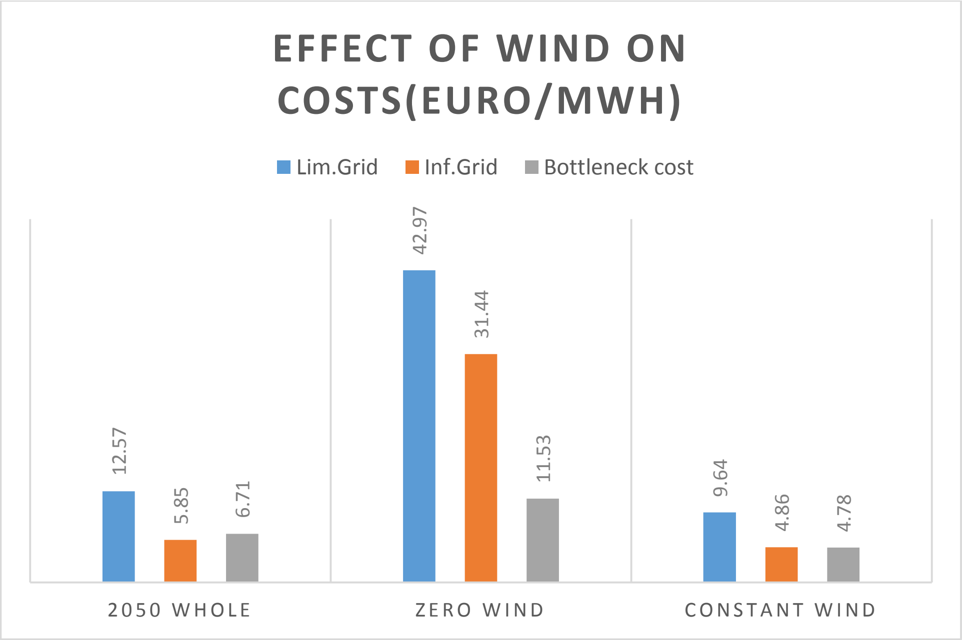


Figure 75 Cost with variable, constant and zero wind power production

In the 2050 whole scenario the wind decreases the total congestion costs with 4.82 Euro/MWh. In the 2050 wind and solar scenario the bottleneck costs is 5.93 Euro/MWh, and the total cost for both limited and infinite grid are lower than for the 2050 whole scenario. This is because there is a higher amount of installed generation capacity than in the 2050 whole scenario. The bottleneck costs with zero wind in the 2030 base scenario was 1.64 Euro/MWh, this is a lot lower than in the 2050 whole scenario. The reason why the bottleneck cost is so high with zero wind in the 2050 whole scenario is that the load shedding with limited grid is 2.09% of the total load and the load shedding with infinite grid is 0.0154%. This can cause this difference in bottleneck costs because the price of load shedding is 375 Euro/MWh, with a load shedding of 2,09% of the load this is a total cost of 32 billion Euros.

Making the wind constant reduces the congestion costs with 1.93 Euro/MWh. This is logical since the highest peaks and bottoms of the wind production are avoided, this gives less stress on the grid.

Effect of solar on costs

In this section the effect the solar power has on the costs and on the bottleneck costs are evaluated for the 2050 whole scenario.

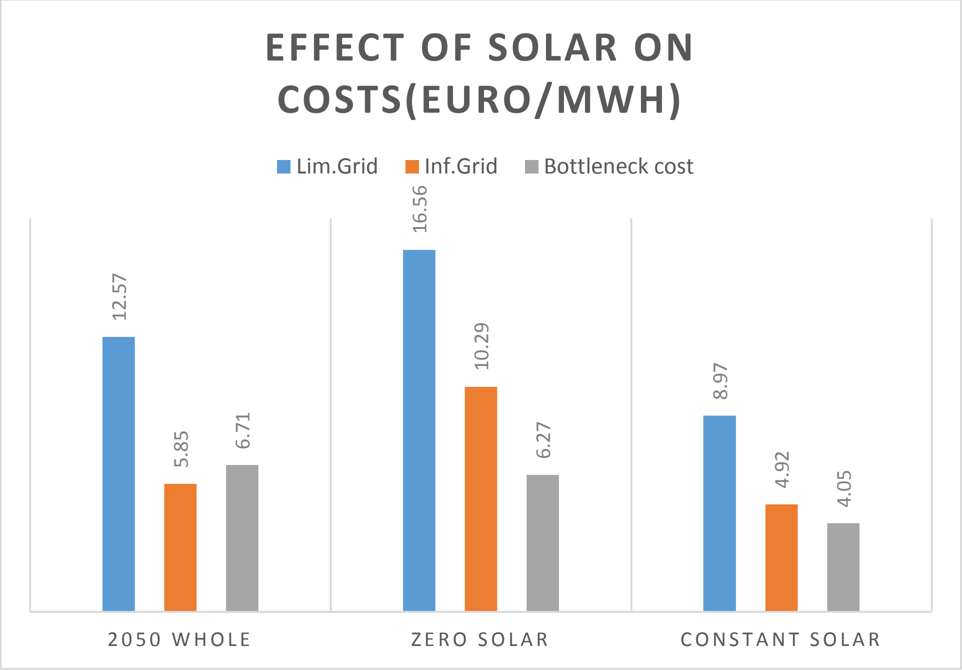


Figure 76 Cost with variable, constant and zero solar power production

The costs are substantially higher without any solar capacity, but the costs are far from being as high as with zero wind, meaning that removing the solar would not increase the costs as much as removing the wind. The solar only cause an increase in congestion costs of 0.44 Euro/MWh. This is natural since there is a higher amount of installed wind and the wind has a much higher utilisation time. Setting the solar to zero will also give less load shedding than setting the wind to zero, therefore the congestion costs are lower with zero solar than with zero wind.

It is interesting that constant solar leads to such low costs. With limited grid the cost is actually lower with constant solar and varying wind than it is with varying solar and constant wind. The bottleneck costs are also lower with constant solar than with constant wind. This shows that making the solar constant can be more beneficial when it comes to overall costs and grid costs. This is probably because the solar produces the most when the load is at its lowest, while the wind peaks are more distributed throughout the year and might fit better to the load pattern.

Effect of wind and solar

Next the effect of both the wind and solar production on the congestion costs are found by finding the costs and bottleneck costs both with zero wind and solar and with constant wind and solar.

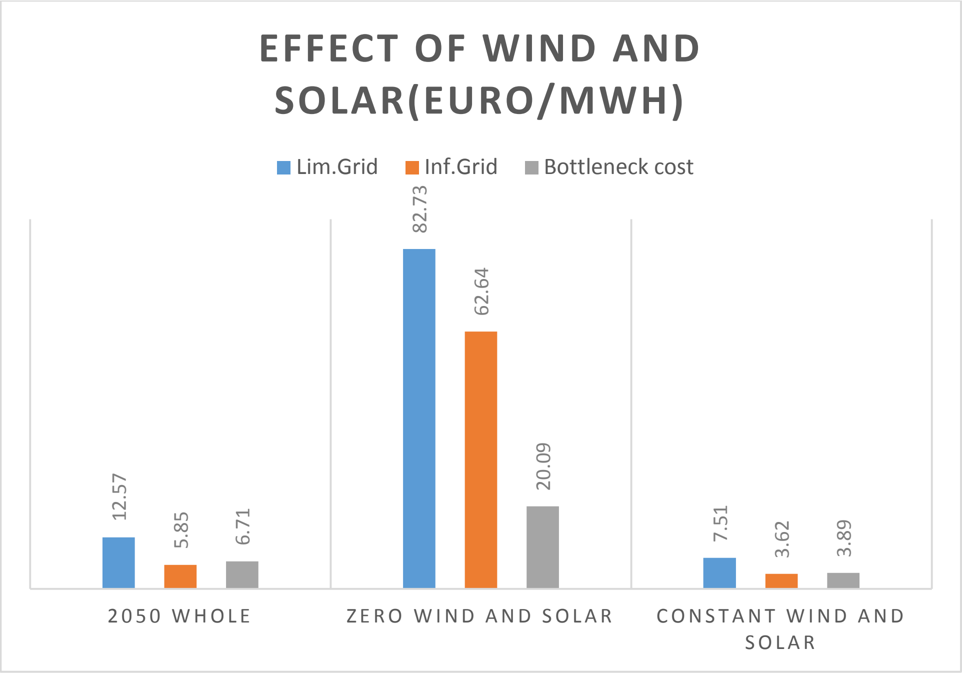


Figure 77 Cost with variable, constant and zero wind and solar power production

The diagram shows that the wind and solar combined decrease the bottleneck costs with 13.38 Euro/MWh. This is very different from the 2050 wind and solar scenario where the wind and solar combined contributes to increasing the bottleneck costs with 2.92 Euro/MWh.

The reason for the high bottlenecks cost with zero wind and solar is that for the 2050 whole scenario with limited grid and zero wind and zero solar the total amount of load shedding is 278.15 TWh, which is 7.08 percent of the total load. For the 2050 wind and solar scenario with zero wind and solar and limited grid the total amount of load shedding is 9.92 TWh, which is 0.236 percent of the total load. This proves that there is a lot more load shedding in the 2050 whole scenario than it is in the 2050 wind and solar scenario. To see if this can be the explanation to some of the difference in bottleneck costs the load shedding with infinite grid is found for the two scenarios as well. In 2050 wind and solar, with zero wind and solar and infinite grid, which is basically the same as 2030 base without any solar or wind the load shedding with infinite grid is zero. This means a reduction of load shedding of 9.92 TWh for the 2050 wind and solar scenario. For the 2050 whole scenario with infinite grid the load shedding with zero wind and solar is 113.01 TWh. This means a difference of 165.14 TWh of load shedding. To see how much difference this can cause in average cost the following equation is solved in matlab:

$$Av.Cost\ of\ Load\ Shed = \frac{Total\ amount\ of\ load\ shedding(MWh) \times Rationing\ price(\frac{Euro}{MWh})}{Total\ load(MWh)}$$

The average cost of load shedding is found first with limited grid and then with infinite grid to see how much the load shedding might contribute to the bottleneck costs in each case. For the 2050 wind and solar scenario with zero wind and solar the average cost of the change in load shedding from limited grid to infinite grid was 0.8859 Euro/MWh. In the 2050 whole scenario the average cost of the change in load shedding between the limited and the infinite grid case was 15.75 Euro/MWh. This means that the cost of the load shedding explains the change in bottleneck costs between the 2050 wind and solar scenario and the 2050 whole scenario.

In the figure below the congestion cost for each simulated scenario for the 2050 whole is summed up.

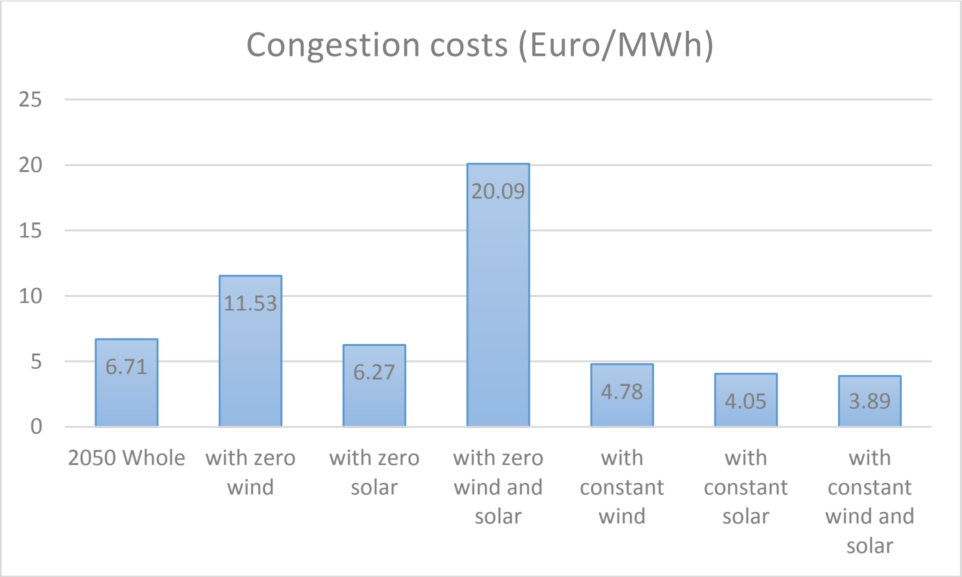


Figure 78 Congestion costs for all scenarios simulated for 2050

The diagram shows that the congestion costs are higher with zero wind than with zero solar. Setting the wind to zero increases the bottleneck costs while setting the solar to zero reduces the bottleneck costs. This is due to the high amount of load shedding when setting the wind to zero. Also making the solar constant reduces the bottleneck costs more than making the wind constant.

4.3.10 Effect of congestions on prices

The figure below shows how much the grid limitations influence the prices, by finding the price with infinite grid minus the price with limited grid.

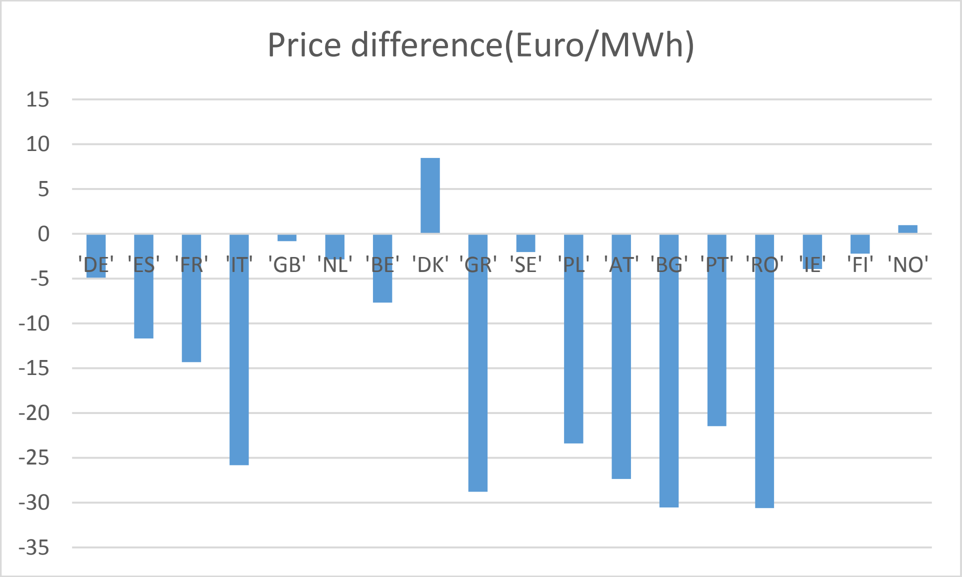


Figure 79 Price(infinite grid)-Price(limited grid)

The figure shows that it is only Denmark and Norway that has an increase in price with infinite grid, the other countries has a decrease. Meaning that making the grid infinite will lower the price in almost all areas. This is because more of the available capacity can be utilized with the infinite grid compared to the limited grid. The effect of the geographical smoothing is also stronger with infinite grid compared to the limited grid case. Denmark and Norway that has a price increase have the lowest prices with limited grid, due to the high availability of hydro power in Norway and the high amount of wind in Denmark. When this has to be shared with the other countries the prices increase.

4.3.11 Possible improvements of the HVDC grid to fit the 2050 whole scenario

In this section the utilisation of the HVDC cables are considered and it is briefly discussed which cables that it could be beneficial to strengthen based on the results found for the 2050 whole scenario. The capacity of some of the cables were increased to account for the increase of wind power in the case of split wind farms, these are the lines between Belgium and Great Britain, Sweden and Poland, Great Britain and Ireland and Germany and Sweden. All of these lines have a total utilisation that is well below 80 percent and it is therefore considered to be unnecessary to strengthen any of these. Below follows a table with the cables where the utilisation is higher than 90 percent, these are the cables where it could be beneficial to increase the transmission capacity.

		Capacity	Utilisation(%)		
From	To		Total	From-To	To-From
NO	GB	1400	95.39	45.80	49.59
NL	NO	1400	96.78	3.29	93.50
DE	NO	1200	92.49	15.57	76.92
NL	GB	1290	95.30	74.45	20.85
FR	GB	5000	90.01	24.11	65.89
FR	IE	1000	93.44	32.98	60.46
West DK	NL	700	99.03	96.36	2.67
East DK	DE	550	93.28	53.93	39.35
SE	DK	485	96.43	14.26	82.16

Table 32 HVDC cables with utilisation of more than 90%

The cable that is the most congested of all is the cable between West DK and the Netherlands and almost exclusively from West DK to the Netherlands. In addition to the HVDC cables between countries one more cable has been addressed earlier, namely the cable between West and East Denmark. In the 2030 Base scenario West DK had a very low mean price and much lower than the mean price in East DK. For the 2050 whole scenario the mean price in West DK is 6.05 and the mean price in east DK is 17.91 indicating that there is unsufficent transmission capacity between the two zones. The utilisation of this cable is found to be 97.7 percent, and the duration curve of the cable is found below.

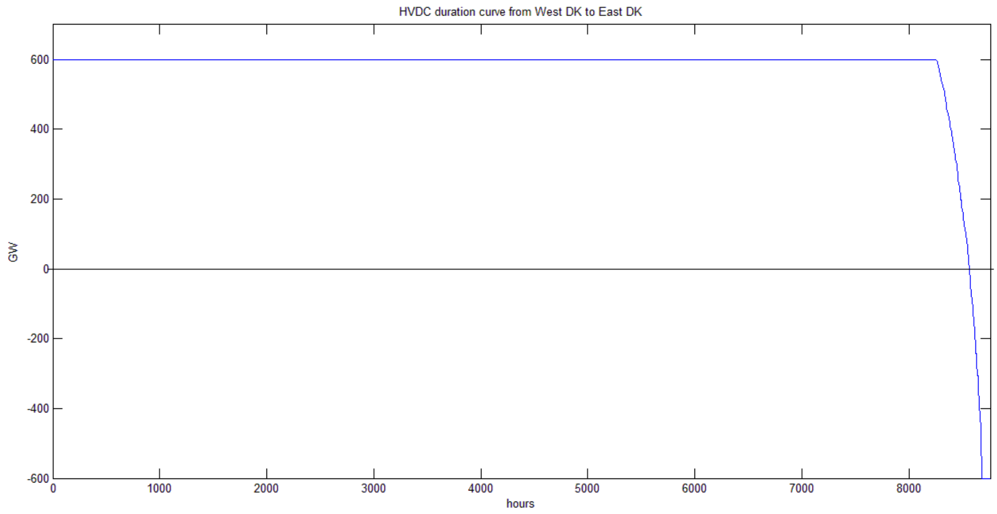


Figure 80 Duration curve for the HVDC-cable for West-DK to East DK

The figure shows that the flow is almost exclusively from West Denmark to East Denmark which is not surprising when looking at the difference in mean price between the two zones. The utilisation of the cable is very high, so it is likely that it would be beneficial to increase the capacity of this line.

5 Conclusions

The wind power capacity is changed from 344.25 GW in the 2030 base to 1024.2 in the 2050 wind scenario. The solar power is increased from 201 GW in 2030 base to 603 GW in the 2050 solar scenario. The utilisation times of both the wind and the solar power decrease when the capacities are increased. The main explanation for this is that the grid restrictions limit the production more when the capacities are increased. Simulations were also done with infinite grid. These results showed that another explanation for the reduction in utilisation time is that some of the wind and solar are turned off for some hours. This is because the potential wind and solar production sometimes exceeds the load. Still it is the limitations in the grid that causes the highest reduction in utilisation time. In the 2030 base scenario the highest reduction in utilisation due to grid restrictions were for Great Britain and was 186 hours. When increasing the wind power to 2050 level the highest reduction in utilisation time was for Denmark and it was 1444 hours. This is almost 8 times higher than the highest reduction in the 2030 base scenario, showing that the grid limitations has enormous effects on the utilisation of wind power. In the 2030 base scenario the reduction in solar utilisation time was highest in Denmark where it was 19 hours. When the solar power was increased to 2050 level the highest reduction was in Germany where it was 243 hours. This is almost 13 times higher than in the 2030 base scenario. Showing that also for solar power the grid restrictions limit the production when the capacities are increased.

The production from fossil fuel plants is highest for the 2030 base scenario and decreases as the amount of renewable energy increases. The same is also true for the nuclear power plants, although the utilisation time is much higher due to the stability of the production and the low marginal costs. In the 2030 Base scenario the total fossil fuel production constitutes 33.16% of the total production. Increasing the wind power to 2050 level reduces this to 16.28%. Increasing the solar power to 2050 level reduces the percentage of fossil production to 24.59%, while increasing both the wind and solar to 2050 level decreases the share of fossil to 11.45%. This shows that increasing the amount of RES reduces the production from fossil plants and therefore also the CO_2 emissions. In the 2050 whole scenario some changes are made to the thermal production in addition to the increase of wind and solar capacities to 2050 level. The fossil production is reduced with totally 152 GW, the nuclear power is reduced with 63.55 GW and the biomass is increased with 112.6 GW. The figures below show the share of production from the RES sources including wind, solar, hydro and biomass and the share of production from non-RES including fossil and nuclear plants.

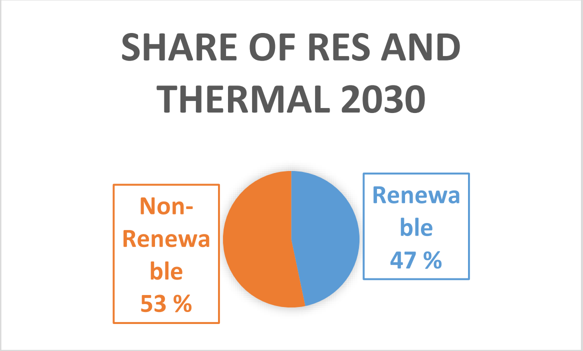


Figure 81 Renewable power share in 2030

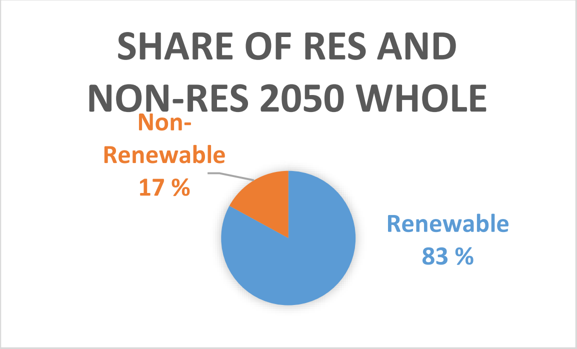


Figure 82 Renewable power share in 2050

The figures show that in the 2050 whole scenario the overall RES production has increased its share to 83%. This is in consistence with the goals set in the energy roadmap 2050 [2].

For most countries the mean price is highest for the 2030 Base scenario with the least amount of RES and lowest for the 2050 wind and solar scenario with the highest amount of RES. In the 2030 base scenario the prices are lowest for the Nordic countries due to the low demand and the high availability of hydro power. Great Britain has the second lowest price following the Nordic countries, while the continental and Eastern European countries have higher prices. Increasing the wind and solar power strongly reduce the prices in all countries. With the wind power at 2050 level, Great Britain which has a high amount of offshore wind power actually achieve the same price level as in the Nordic countries.

The flow over the HVDC cables are investigated in detail. The flow on the HVDC cables in the 2030 Base scenario are explained in the following. The prices are lowest in the Nordic countries and the flow on the HVDC lines between the Nordic countries and the continental countries goes almost exclusively from the Nordic countries to the continent. Almost all the flow on the HVDC cable between Norway and Great Britain goes from Norway to Great Britain. The HVDC cables connecting Great Britain to the continent has almost all of its flow from Great Britain to the continent. The following map shows the flow on the HVDC corridors connecting the different countries, the flow in the 2030 base scenario is shown in grey and the flow in the 2050 whole scenario is shown in red.

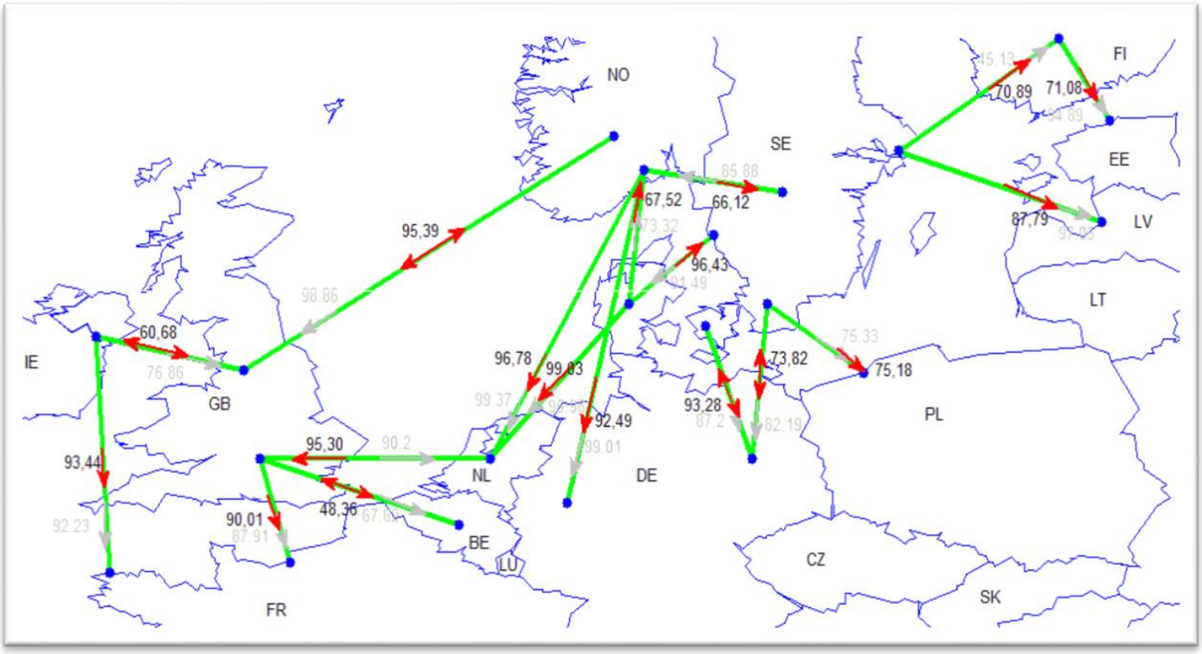


Figure 83 HVDC flow in 2030 base and 2050 whole scenario

When the wind and solar power is increased in the 2050 scenarios the flow pattern over the HVDC cables changes. In all the 2050 scenarios the flow on the HVDC lines goes from being mainly export from the Nordic countries and Great Britain to the continental countries to an increased amount of export from the continent. This effect is strongest for the 2050 solar scenario, because almost all the increase in solar is in the continental countries. The same effect is also seen in the 2050 wind scenario, but to a lower extent since the increase of wind power also affects the Nordic countries and Great Britain. In the 2050 wind and solar the effect can be seen more clearly than in the 2050 wind scenario, but not as much as in the 2050 solar scenario. When changing the thermal capacities in the 2050 whole scenario the export from the continent to the Nordic countries become a bit lower than in the 2050 wind and solar scenario due to the higher amount of thermal power on the continent. The export from Great Britain to Norway is also slightly reduced compared to the 2050 wind and solar scenario, due to the higher amount of nuclear and fossil power in Great Britain.

The costs and congestion costs are investigated for each scenario with special focus on the effect of the increase of wind and solar capacity to 2050 level. In the figure below the costs and congestion costs for the 2030 base, 2050 wind, 2050 solar and 2050 wind and solar are shown.

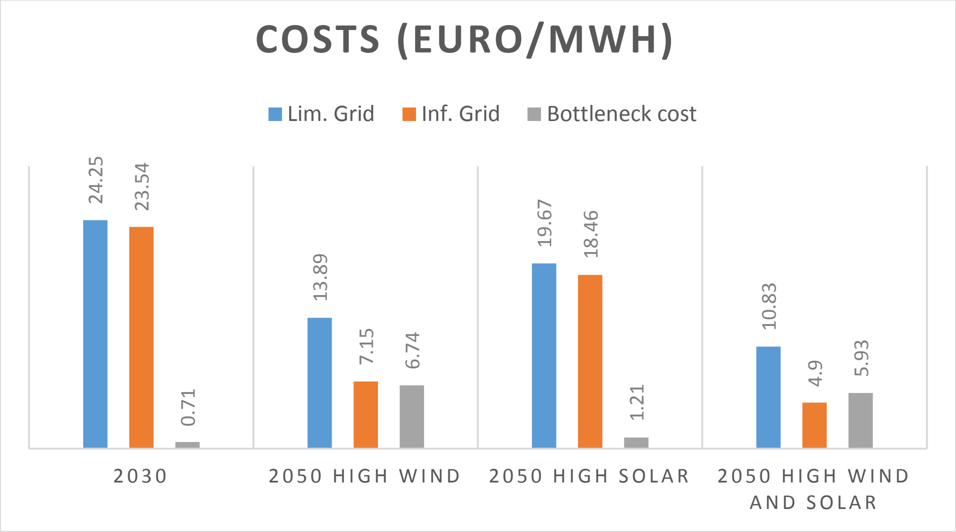


Figure 84 Cost and congestion cost

When it comes to the average costs in the energy system it is highest for the 2030 base, then comes the 2050 solar, then the 2050 wind and at last the 2050 wind and solar scenario. This is natural since this is the order the scenarios would take if they were sorted from the scenario with the least amount of renewable energy to the scenario with the highest amount of renewable energy. The increase of wind and solar to 2050 level has an enormous impact on the average cost. The average cost in the 2030 base scenario is 24.25 Euro/MWh. In the 2050 wind and solar scenario the average cost is only 10.83 Euro/MWh. The explanation for this high decrease in costs is that wind and solar power has low marginal costs and replaces thermal plants with high marginal costs.

The bottleneck costs are lowest for the 2030 base scenario, where it is 0.71 Euro/MWh. When the solar is increased to 2050 level the bottleneck costs increase to 1.21 Euro/MWh. When the wind is increased to 2050 level the bottleneck costs increases a lot more, to 6.74 Euro/MWh. However increasing both the wind and the solar to 2050 level actually gives lower bottleneck costs than increasing only the wind. This is caused by the fact that the combination of wind and solar production gives a beneficial production pattern when it comes to utilizing the grid, the solar power has a beneficial diurnal pattern, while the wind power has a beneficial seasonal pattern. This means that the combination of wind and solar power follow the load pattern better than just the wind power and therefore causes less strain on the grid.

Simulations are also made with constant wind power, constant solar power and constant wind and solar power to investigate the costs of the variability of wind and solar. The variability of the wind power increases the bottleneck costs. This is because the variable wind gives high production peaks and bottoms, which increase the need for export and import and hence the grid becomes more strained. In the 2050 solar scenario with constant solar the congestion costs are less than half of what they are with variable solar power. Making the solar power constant is beneficial because the solar production is high during the summer and low during the winter, which means that the seasonal variation of solar is not beneficial when it comes to following the load. When the solar production is made constant the solar production during the winter becomes higher, and the start-up of expensive thermal plants are avoided. The seasonal variation of solar power is also not beneficial when it comes to the utilisation of hydro reservoirs, since the reservoirs are at its highest level when the solar production is high. This leaves less reservoir capacity available for storage.

There are a lot of AC congestions in the grid and many of the HVDC cables are close to fully utilized. The table below shows the HVDC cables that have utilisations in the 2050 whole scenario of more than 90%, and it is therefore likely that it is economically beneficial to extend the capacity on these cables if such high amount of RES becomes a reality.

		Capacity	Utilisation(%)		
From	To		Total	From-To	To-From
NO	GB	1400	95.39	45.80	49.59
NL	NO	1400	96.78	3.29	93.50
DE	NO	1200	92.49	15.57	76.92
NL	GB	1290	95.30	74.45	20.85
FR	GB	5000	90.01	24.11	65.89
FR	IE	1000	93.44	32.98	60.46
West DK	NL	700	99.03	96.36	2.67
East DK	DE	550	93.28	53.93	39.35
SE	DK	485	96.43	14.26	82.16

Table 33 HVDC cables with utilisation of more than 90%

In addition to these cables the capacity of the HVDC cable connecting West and East Denmark should be extended, since this cable is close to fully utilized and there is a high price difference between the two zones.

6 Further work

In this thesis the capacities of the existing wind and solar plants in the PSST model is first scaled to fit the 2030 dataset from EC for each country and then the capacities for all countries are scaled with the same factor to reach the 2050 capacities from the ENTSO-E energy roadmap. In a more detailed analysis of the 2050 energy system the geographical distribution of the wind and solar plants should be assessed in more detail. Information about the potential wind and solar production at each site should be obtained. For example it is not certain that it is possible to extend a wind farm with three times its original capacity at a given site, for example due to geographical obstacles. In this thesis no economic analysis is performed with regards to the geographical spreading of wind and solar plants. An idea for further work could be to increase the wind and solar power at different geographical locations with different factors instead of just scaling the capacities from 2030 to 2050 level with the same factor. Then an economic analysis could be performed to find the most profitable location of the wind and solar power.

In this work only the grid between country borders are included, except for a few internal lines in the Nordic grid. This is because the simulation could not run with internal grid. An idea for further work is to adapt the internal grid so that this could be included in the simulations. Especially it would be interesting to analyse what effect internal grid congestions would have on the solar production and the wind production. Since solar power is usually located closer to the consumption centres it is likely that the effect of the internal congestions would be smaller for solar power than for wind power, and that the need for grid reinforcements would be less with solar than with wind.

The analysis of congestion costs is a large part of this thesis. As a part of this work simulations were done with constant wind and solar power to see how much the variability of wind and solar power influenced the congestion costs separately or together. This analysis showed that the variability of both wind and solar increased the congestion costs. This opens up for a further analysis of storage possibilities. Making the wind and solar constant for all the year would require a high amount of storage capacity, therefore simulations could also be done with the possibility of making the wind and solar limited for a shorter time span. An economic analysis could be performed of how much storage that is profitable to install at a certain location next to a wind farm or a solar farm. In this work the start and stop costs of thermal plants are not included. This could influence the comparison of the costs with variable and constant wind and solar power. If the costs of starting and stopping thermal plants were included this would increase the costs with variable production because this would lead to more start-up and stops as a response to the variable production.

In this work the HVDC cables that have the highest utilisation in the 2050 scenario are listed, in a further study of the 2050 energy system the profitability of increasing the capacities of these cables could be performed.

In the 2050 scenario the total storable hydro capacity in Norway is 31.4 GW. The Cedren project conducted by Sintef energy research study the possibilities of increasing the hydro capacity in southern Norway. In one of the cases studied it is found that it is possible to expand the existing hydro capacity with 18.2 GW compared to today, amounting to a total hydro capacity of about 48 GW, including pumping [15]. An idea for further studies is to investigate how the increased storage possibilities of such a hydro expansion would influence the profitability of wind and solar power towards 2050.

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Appendix

A.1 Scale wind generation to fit 2030 SO&AF data

This code is much longer, but only the scaling of the german wind farms is included here to show the procedure.

```
load('country');%gives country code of the wind generation nodes
load('windPowerTimeSeries2030');%the original wind power time series found
in PSST dataset from Sintef
load('New_Onshore')%The new onshore capacities for each country
load('New_Offshore')%The new offshore capacity for each country
load('Buses_with_onshore')%The id of the buses that are onshore
load('Buses_with_offshore')%The id of the buses that are offshore

% OnshoreCap=cap;
% OnshoreCap(720:766)=0;
% OnshoreCap=OnshoreCap/1000;

OffshoreCap_bus=zeros(892,1);
for i= 1:length(Buses_with_offshore)

    OffshoreCap_bus(Buses_with_offshore(i))=cap(Buses_with_offshore(i))

end

OnshoreCap_bus=zeros(892,1)
for i=1:length(Buses_with_onshore)
    OnshoreCap_bus(Buses_with_onshore(i))=cap(Buses_with_onshore(i))
end
%


OffshoreCap_bus=OffshoreCap_bus/1000;
OnshoreCap_bus=OnshoreCap_bus/1000;


% gives area ID for each of the 892 wind generators
AreaIDDE=find(country==1);%This is done for all 34 countries
%find original wind generation cap for each country.

OldOnshoreCap=zeros(37,1);

OldOnshoreCap(1)=sum(OnshoreCap_bus(AreaIDDE));%  This  is  done  for  all  34
countries
%finds original offshorecap for each country
OldOffshoreCap=zeros(37,1);

OldOffshoreCap(1)=sum(OffshoreCap_bus(AreaIDDE));  This  is  done  for  all  34
countries
%makes the vector that the old capacities should be multiplied with

changeOnshore=New_Onshore./OldOnshoreCap;
```

```
changeOnshore(isnan(changeOnshore))=0;

changeOffshore=New_Offshore./OldOffshoreCap;
changeOffshore(isnan(changeOffshore))=0;


%Codes that finds the new generation capacity in GW for each generator and
%places it in vector NewOnshore_bus
OnshoreCap_busMW=OnshoreCap_bus*1000;
NewOnshore_bus=zeros(892,1);
%DE
for i=1:length(AreaIDDE)

NewOnshore_bus(AreaIDDE(i))=changeOnshore(1)*OnshoreCap_busMW(AreaIDDE(i));
End%done for all countries
%Finds new offshore gen for each bus
OffshoreCap_busMW=OffshoreCap_bus*1000;
NewOffshore_bus=zeros(892,1);
%DE
for i=1:length(AreaIDDE)

NewOffshore_bus(AreaIDDE(i))=changeOffshore(1)*OffshoreCap_busMW(AreaIDDE(i
));
end

Newcap=NewOffshore_bus+NewOnshore_bus;
```

A.2

The codes for changing the solar capacities in Germany are included, all the other 25 countries with solar is also changed in the same manner.

```
load('C:\Users\Karen\Desktop\Manipulate_solar\CountryCodeSolar.mat')
load('C:\Users\Karen\Desktop\Manipulate_solar\PV_scenarios_COSMO_year_2030.
mat')
load('ENTSOE_Solar.mat')
%
% %Finds Maximum solar production Cosmo må lastes inn først
 maxSolarNode=(max(Ppot))';


 Capacities=zeros(25,1);


CountriesWithSolar={'DE';'NL';'BE';'LU';'FR';'IT';'AT';'ES';'SE';'CZ';'SI';
'GR';'HU';'GB';'PT';'RO';'BG';'SK';'PL';'FI';'DK';'IE';'LT';'EE';'LV'};

 DESolar=find(CountryCodeSolar==1);
Capacities(1)=(sum(maxSolarNode(DESolar)))/1000;
ChangeVector=ENTSOE_Solar./Capacities;
NewPpot=zeros(8760,1381);

for i=1:length(DESolar);
    NewPpot(:,DESolar(i))=ChangeVector(1)*Ppot(:,DESolar(i));
end
newMaxSolar=max(NewPpot);
```

```
NewCapacities(1)=(sum(newMaxSolar(DESolar)))/1000;
```

A.3 The scaling of the wind power times series to 2050 level

```
OffshoreCap_bus=zeros(892,1);

for i= 1:length(Buses_with_offshore)

    OffshoreCap_bus(Buses_with_offshore(i))=cap(Buses_with_offshore(i))

end

OnshoreCap_bus=zeros(892,1);
for i=1:length(Buses_with_onshore)
    OnshoreCap_bus(Buses_with_onshore(i))=cap(Buses_with_onshore(i))
end

sumOffshoreCap=(sum(OffshoreCap_bus))/1000;
sumOnshoreCap=sum((OnshoreCap_bus))/1000;

RefChangeOnshore=2.59;
RefChangeOffshore=3.824;

NewOnshoreCap=RefChangeOnshore*OnshoreCap_bus;
NewOffshoreCap=RefChangeOffshore*OffshoreCap_bus;

NewCap=NewOnshoreCap+NewOffshoreCap;
```