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Assessing impacts on energy flows and CO_2 emissions due to an alteration of interconnection topology between Norway and the UK

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Summary

The world is today facing one of the most pervasive and threatening crises of all time in terms of climate changes. Excessive CO_2 emissions are posing a significant challenge to the sustainable development of human society [78]. As a matter of fact, carbon emissions originates from many different sources. While electricity makes up less than 20% of the worlds total energy consumption, almost 40% of the global CO_2 emissions are attributable to the electricity sector [39]. Thus, in line with the ever-increasing electrification of industry, transport and agriculture, it is apparent that decarbonization of the electric power industry is a topic of high importance.

Promoting sustainable development and reducing carbon emissions have become integrated aspects of energy planning, analysis and policy making in many countries. An increasing number of parties from all levels of the society are involved in the carbon mitigation initiative. Hence, it becomes crucial to clarify and identify to which extent different parties are accountable for CO_2 emissions [48] [44]. Doing so requires the establishment of effective methods for calculation and analysis of carbon emissions in the power system. A useful tool in this context is power flow tracing, which can be used to support qualitative ideas with quantitative analyses of power flows in the grid.

Indeed, to ensure meeting climate targets without sacrificing security of supply and grid stability, the European grid is getting more and more meshed and interconnected [23]. Several large-scale transmission projects are under construction or planned in Europe. Amongst them is a projected sea cable that is intended to interconnect the Norwegian grid with the Scottish. The construction of this interconnecting resource has, the last year, been a controversial topic in the Norwegian political landscape. An economic assessment provided by The Norwegian Water Resources and Energy Directorate (NVE) concluded that the increased exchange capacity due to this cable would be socioeconomic profitable. However, the environmental effects regarding carbon emissions following the cable were not accounted for. Consequently, this thesis sets out to investigate, through both qualitative discussions and quantitative simulations, the environmental footprint of a similar, generic, cable - hereafter denoted as the UK-N cable. Doing so involves indeed examining the impact such a cable has on power production, power flows and power prices.

In order to provide a more nuanced view of the possible outcomes following the implementation of the UK-N cable, two different scenarios are built and simulated for the year 2040. One scenario, *2040 - Current Policy*, is mainly based upon EU's "Reference Scenario 2016" which forecasts the future development of the European power grid. The other scenario, *2040 - Wind&Solar*, emphasise to greater extent the development of renewable power production and increased power surplus in Norway, Sweden and the UK. Both scenario simulations show that the UK-N cable mitigate overall carbon emissions in the simulated system.

In scenario *2040 - Current Policy*, the reductions in CO_2 emissions are mostly found in the UK where Norwegian hydropower displaces thermal power, giving a reduction of almost 1Mton. These savings are, however, to large degree offset by the fact that the increased power trade with UK makes Norway export less hydropower on exiting interconnections to countries like Germany and the Netherlands. Also Poland has a significant rise in domestic emissions - being more than 0,4 Mton. This is the same order of magnitude as the increase seen in Germany. Power flow tracing shows that this is mostly due to the fact that the implementation of the UK-N cable makes less power from Norway, Sweden and Denmark reach the polish energy market. Consequently, the distributional effects following the UK-N cable tend to increase the domestic CO_2 emissions in countries interconnected to Norway, and do also impact the the emission level in other countries on Continental Europe. In total, the reduction in CO_2 emissions for the whole system is of 0,05 Mton.

In scenario *2040 - Wind&Solar*, on the other hand, the emission levels reduce in multiple countries following the UK-N cable. This effect accounts for both the UK, most of the other countries interconnected to Norway and in numerous countries on Continental Europe. Interestingly, the reduced CO_2 emissions in the UK is around 0,4 Mton - less than half of what is found in the other scenario. Overall mitigation of CO_2 emissions is nevertheless of 1,3 Mton.

Both scenarios show that the UK-N cable leads to reduced net export on existing interconnections from Norway. Nevertheless, the total net export from Norway increases following the UK-N cable. The simulations show that in scenario *2040 - Current Policy* and *2040 - Wind&Solar* the UK-N cable yields, on average, increased power prices of 2,2 €/MWh (3,5%) og 0,6 €/MWh (1%), respectively.

Sammendrag

Klimaforandringer utgjør i dag en av de mest gjennomgripende og truende krisene verden noen gang har stått overfor. Store CO_2-utslipp utgjør en betydelig utfordring for verdens bærekraftige utvikling [78]. Det er mange kilder til karbonutslipp. Et av de viktigste er kraftsektoren, som til tross for å dekke mindre enn 20% av verdens energiforbruk, står for omtrent 40% av de globale CO_2-utslippene [39]. Som følge av økt elektrifisering av industri, transport og jordbruk, blir det enda viktigere å vektlegge utviklingen av en fremtidig kraftindustri som avgir mindre CO_2-utlipp.

Å fremme bærekraftig utvikling har blitt integrerte aspekter ved energiplanlegging, analyser og utforming av politikk i mange land. Ettersom stadig flere aktører fra alle samfunnslag involveres i klimaspørsmålet, er det nødvendig å kunne tydeliggjøre i hvor stor grad ulike aktører står ansvarlige for CO_2-utslipp [48]. Dette krever at man etablerer effektive metoder for beregning og analyse av karbonutslipp i kraftsystemet. Et nyttig verktøy i denne sammenhengen er kraftflytsporing ("power flow tracing"). Dette verktøyet kan brukes til å støtte kvalitative ideér med kvantitative analyser av kraftflyt i nettet.

For å nå fastsatte klimamål uten at det går på bekostning av forsyningssikkerhet og nettstabilitet blir det europeiske kraftnettet stadig mer sammenvevd [23]. Flere storskala kraftoverføringsprosjekter er under konstruksjon og planlegging i Europa. Blant dem er en prosjektert sjøkabel som skal forbinde det norske kraftnettet med det skotske. Byggingen av denne overføringskabelen har det siste året vært et kontroversielt tema i det rikspolitiske miljøet i Norge. En økonomisk evaluering fra NVE konkluderte med at den økte utvekslingskapasiteten denne kabelen bringer ville være samfunnsøkonomisk lønnsom. Effektene denne kabelen har med hensyn til CO_2-utslipp ble det ikke gjort rede for i rapporten. Følgelig har denne avhandlingen som mål å undersøke, gjennom både kvalitative diskusjoner og kvantitative simuleringer, miljøfotavtrykket til en slik kabel - heretter kalt UK-N-kabelen. Dette krever nødvendigvis at også kabelens innvirkning på kraftproduksjon, kraftflyt og kraftpriser blir undersøkt nærmere.

For å gi et mer nyansert bilde av mulige konsekvenser ved implementeringen av UK-N-kabelen simuleres det to ulike kraftsystem-scenarioer for år 2040. Det ene scenarioet, *2040 - Current Policy* er hovedsakelig basert på EUs "Reference Scenario 2016", som gir en prognose av den framtidige utviklingen til det europeiske kraftnettet. Det andre scenarioet, *2040 - Wind&Solar*, vektlegger i større grad utbygging av fornybare energikilder i Norge, Sverige og Storbritannia. Dette scenarioet gir et høyere kraftoverskudd for de nevnte landene. Begge scenariosimuleringene viser at UK-N-kabelen gir reduserte CO_2-utslipp i det simulerte systemet.

I scenario 2040 - Current Policy reduseres de totale CO_2-utslippene med nærmere 1 Mtonn. Det meste av denne reduksjon kan tilskrives Storbritannia, hvor norsk vannkraft erstatter

termisk kraft. Disse besparelsene utlignes imidlertid i stor grad av at den økte krafthandelen med Storbritannia medfører mindre eksport av norsk vannkraft over de øvrige utvekslingsforbindelsene fra Norge, spesielt til land som Tyskland og Nederland. Indirekte blir også Polen berørt av dette - her er økningen i innenlandske utslipp på 0,4 Mtonn som følge av UK-N-kabelen. Dette er i samme størrelsesorden som utslippsøkningen i Tyskland. Sporing av kraftflyt indikerer at økningen i polske utslipp først og fremst skyldes at implementeringen av UK-N-kabelen fører til at mindre kraft fra Norge, Sverige og Danmark når det polske kraftmarkedet. Det kan derfor konkluderes med at blant følgeeffektene av UK-N-kabelen ser man at andre land direktekoblet Norge øker sine utslipp, i tillegg til at også utslippsnivået i Fastlands-Europa påvirkes. I dette scenarioet ender CO_2-besparelsene for hele systemet på totalt 0,05 Mtonn.

I scenario *2040 - Wind&Solar* derimot, minsker utslippsnivåene i en rekke land som følge av UK-N-kabelen. Denne effekten sees i både Storbritannia, majoriteten av land direktekoblet til Norge og i flere land i Fastlands-Europa. De innenlandske CO_2-besparelsene i Storbritannia viser seg derimot å være på rundt 0,4 Mtonn - mindre enn halvparten av hva som ble funnet i det andre scenarioet. Den totale reduksjonen i CO_2-utslipp beregnes til 1,3 Mtonn.

Begge scenarioene viser at UK-N-kabelen fører til redusert nettoeksport på de øvrige utvekslingsforbindelsene fra Norge. UK-N kabelen fører likevel til at Norges totale nettoeksport øker. Simuleringene viser at i scenarioene *2040 - Current Policy* og *2040 - Wind&Solar* resulterer UK-N kabelen i gjennomsnittlig økte strømpriser i Norge på henholdsvis 2,2 €/MWh (3,5%) og 0,6 €/MWh (1%).

Acknowledgment

This Master's thesis concludes my Master of Science within Energy and Environmental Engineering at the Department of Electric Power Engineering at NTNU in Trondheim. The thesis sets out to address, through power system simulation and power flow tracing, some of the implications found when altering the topology of the European grid. It is my hope that this thesis can highlight some of the benefits when utilizing the powerful tool of power flow tracing and inspire to further dedicated research within this field!

I would like to express my sincere gratitude to my supervisor Professor Magnus Korpås for his excellent guidance and everlasting positivity. The enthusiasm he expresses for the study of power systems - as well as for me and my realization of this thesis - has been a great source of inspiration!

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Last but not least, thanks to my friends and family for always being by my side.

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Abbreviations

CCS	=	Carbon capture-and-storage
EFI	=	Elektrisitetsforsyningens Forskningsinstitutt
EGT	=	Electricity generating technology
EMPS	=	EFI's Multi-area Power-market Simulator
ENTSO-E	=	European Network of Transmission System Operators for Electricity
IEA	=	International Energy Agency
MA	=	Moving averages
MRIO	=	Multi-regional input-output
NC	=	North Connect cable
NOA	=	Network Options Assessment
NVE	=	The Norwegian Water Resources and Energy Directorate
PCI	=	Project of Common Interest
PFT	=	Power flow tracing
PV	=	Photovoltaic
RES	=	Renewable energy systems
TSO	=	Transmission System Operator
USF	=	Unscheduled flows
VRES	=	Variable renewable energy systems

Chapter 1

Introduction

1.1 Motivation

Carbon emissions from human activity are one of the main driving forces for the climate changes seen nowadays [92]. The emissions come from many sources, where the electricity sector is a major contributor to the total inventory of these emissions. However, there are significant variations in the impacts associated with different electricity generation technology. While electric power from non-renewable sources contributes to large amounts of greenhouse gases, renewable power sources, on the other hand, have considerably lower impacts. In order to assess the carbon footprint of consumed electricity, it is therefore crucial to have insight in the different places of origin of the electric power.

Existing methods for calculating and analyzing carbon emissions in the power sector mainly focus on emissions related to power generation. This approach is typically found in statistical analysis [7] and life cycle analysis [95]. The power generation sector is undoubtedly the main source of carbon emissions in a power system, as emissions associated with transmission and consumption are negligible. Nevertheless, power generation is driven by demand, implying that electricity consumers could be considered as the primary cause of carbon emissions. Put in other words, to establish a platform of fair allocation of emissions the generating parties should be identified from the perspective of the consuming parties. One way to do this is by means of power flow tracing and corresponding CO_2 allocation.

With the increasing complexity of the modern electrical grid and shift towards a more sustainable power generation, higher system flexibility is crucial due to today's and tomorrow's, need for constant access to electrical energy. Flexibility can be denoted as the ability a power system has to respond to changes in power demand and production [50].

The integration of large shares of variable renewable energy systems (VRES), in particular wind and solar, can lead to increased requirements regarding flexibility for the complementary power system. Geographical dispersion of renewable power plants through increased interconnection capacity is one of many methods to provide system flexibility and stability [37]. The Norwegian generation portfolio consists mostly of hydro power facilities, which offer highly flexible production to relatively low cost as well as the possibility of storing energy in the form of hydro reservoirs [33]. This makes Norway an eminent balancing agent in the European power market. As of 2020, Norway has operative interconnections with five neighbouring countries (Sweden, Denmark, Finland, the Netherlands and Russia). Moreover, two more interconnections are under construction to the UK and Germany, respectively.

Keeping in mind the fact that the European grid is getting more and more connected several questions arise;

- Do new interconnections actually contribute to lower CO_2 emissions and domestic CO_2 intensity?
- Is the exported power used for balancing and consumption at receiving-end, or does it transit further?
- How does a new interconnection affect the power prices at both ends?

This thesis will, by means of power market simulations and power flow tracing, contribute to clarify some of these questions.

1.2 Organization of thesis

The thesis is divided into the following chapters:

Chapter 2: Reviews some crucial aspects regarding power system operation and balancing. Emphasizing the introduction of high shares of variables RES in the power grid alongside reinforcement of the power grid through increased interconnection capacity.

Chapter 3: Examines previous reports assessing implications following a new interconnection cable between Western Norway and Scotland.

Chapter 4: Presents firstly the concept of power flow tracing and its applications. Thereafter the so-called MRIO methodology is explained. This approach forms the basis of the power flow tracing algorithm utilized in this thesis. Lastly, the applied method for CO_2 emission apportioning is shown.

Chapter 5: Introduces the EMPS model, which is the numerical simulation tool utilized in this thesis. This is an optimization model that sets out to maximize the expected value of total economic surplus for the given power system.

Chapter 6: Explains major assumptions and premises for the simulations, alongside other exogenous input variables that are considered relevant. There are built two different scenarios; one based on EU's Reference Scenario for the development of the European power grid and one which extends this reference scenario with increased RES production and increased power surplus in Norway, Sweden and the UK. Both scenarios are simulated with and without the cable from Western Norway to Scotland (called the UK-N cable), giving a total of four simulations.

Chapter 7: Documents the simulation results for all four simulations from the EMPS. Results from power flow tracing are also presented.

Chapter 8: Discusses the findings from the simulation, emphasizing the power exchange, environmental aspects and price variations. Lastly, uncertainties regarding various aspects of the study are reviewed.

Chapter 9: Provides final conclusions from what has been simulated and reviewed. Challenges when conducting an investigation of larger energy systems are being remarked and recommendations for future work are denoted.

Chapter 2

Literature Review

2.1 General

The reduction of carbon emissions is a topic of international concern. Recent years have witnessed a fundamental change in the way nations and industries approach energy-related environmental issues. In order to mitigate the climatic changes, the UN Framework Convention on Climate Changes was created in 1992 to act as a platform of discussion and agreements. Most recently, from the Paris Agreement, which took effect in 2016, the international community acknowledged the common goal of preventing the world's average temperature of increasing more than 2^{o}C compared to the pre-industrial level [91]. To achieve this goal, the Paris Agreement calls for emissions to peak as soon as possible and reduce thereafter. The International Energy Agency (IEA) has proposed a scenario model, called the Sustainable Development scenario, which is fully aligned with the Paris Agreement. Figure 2.1 shows the share of global electricity generation by source for the IEA Sustainable Development scenario [41].

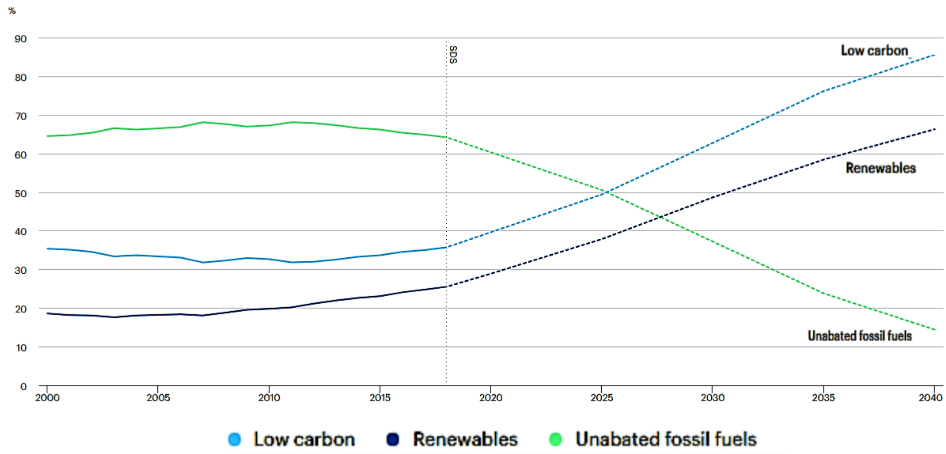


Figure 2.1: Global electricity generation by source presented by IEA [41]. Bear in mind that "Low carbon" accounts both for renewable power generation, nuclear power production and fossil power plants utilizing carbon capture-and-storage (CCS).

Traditionally, thermal power plants based on fossil fuels have been the primary source of the worlds electric power production. Nowadays, the world is experiencing a green shift, where the implementation of renewable energy has been steadily increasing. From 2014 the share of renewables in the worlds net annual addition of power generation has been above 50% [65]. As of 2018, approximately 60% of the worlds annual added power generation was based on renewable resources. Despite this trend shift, critical voices have proclaimed that the development is going too slow compared to what the international society has agreed upon [93]. Figure 2.2 shows the global investments in different generating technologies since 2005.

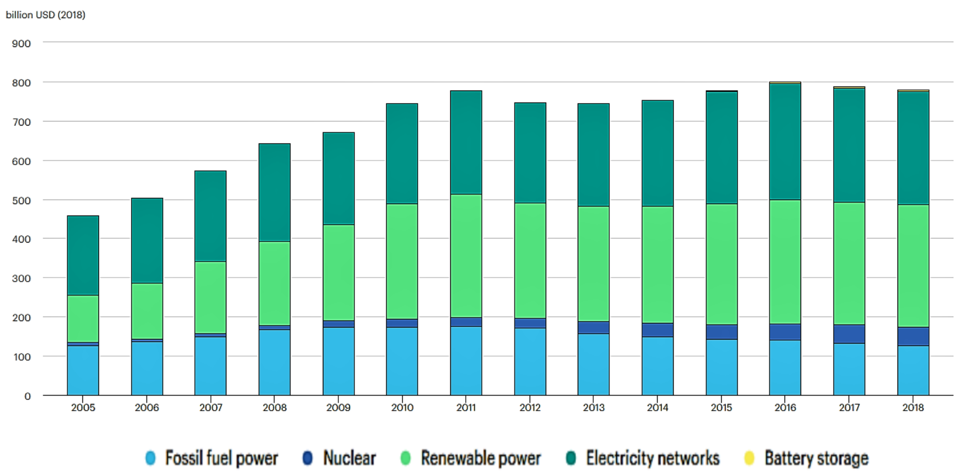


Figure 2.2: Share of global investment in electric energy systems [41] [42].

2.2 Power system operation and stabilisation

The integration of asynchronous renewable sources, like solar power plants (photovoltaic (PV) plants) and most wind power plants, brings many benefits to the electric power grids. However, there are also various drawbacks that follow their implementation into the grid [19] [105]. The latter applies first and foremost to operation, modelling and dynamic performance of the power systems with high shares of RES. This, alongside some of the economic impacts seen from implementation of VRES and interconnections in the power system, will be emphasised in this section.

2.2.1 Increased penetration of asynchronous and inverter-based power generation

The power system frequency is of today the best single-parameter to indicate load-generation balance and, thus, overall stability in the power system. Maintaining a near-constant frequency is the paramount role of the power system operator [36]. Nonetheless, in line with the ever-increasing share of generating facilities based on renewable resources, the total level of rotational inertia in the power grid is decreasing. The kinetic energy stored in rotating masses in conventional synchronous generators is essential to limit frequency disturbances in the grid. The dynamics of the rotating mass, called the rotor dynamics, are directly coupled with the power grid frequency [28]. Overall, the suppression of frequency disturbances done by synchronous generators is called the inertial response.

However, most VRES plants are often connected to the grid by means of power converters and/or induction (asynchronous) generators. Hence, they lack the property of rotational inertia seen by the grid. Whereas solar plants have no rotating mass whatsoever, wind power plants have, on the other hand, rotating mass in terms of its turbines. Nevertheless, since induction generators are the most widespread technology in wind power plants, the rotational inertia is not directly coupled to the grid [106] [107]. However, there are ways to emulate the inertial response in VRES through control mechanisms for operation and power converters. The latter goes under the descriptive name of "synthetic inertia", and the motivated reader is referred to [30] by A. Storruste and O. M. Forbord for a more thorough introduction within this field of study.

Eventually, there are several other challenges also following the integration of high share RES into the power system. First of all, wind and solar power differs from dispatchable conventional thermal and hydropower plants in the way that their availability is only partially predictable. Accordingly, large shares of their supply remain stochastic. Figure 2.3 shows a generic schematic of the stochastic availability of wind energy and solar irradiation. At times of with little wind and low solar irradiation, compensating power must be added to the grid. Secondly, marginal costs of variable renewable energy are close to zero. Consequently, there are unresolved challenges concerning how future financial principles within the power market could facilitate the trade of energy and use of ancillary services. The variable and uncertain nature of generation alongside digitalization on consumer-end might also open up demand-side flexibility as a process for dispatching and thus balancing [36] [35]. Other challenges of major importance following the increased penetration of VRES are: power system stiffness, capabilities for black start and means of protection.

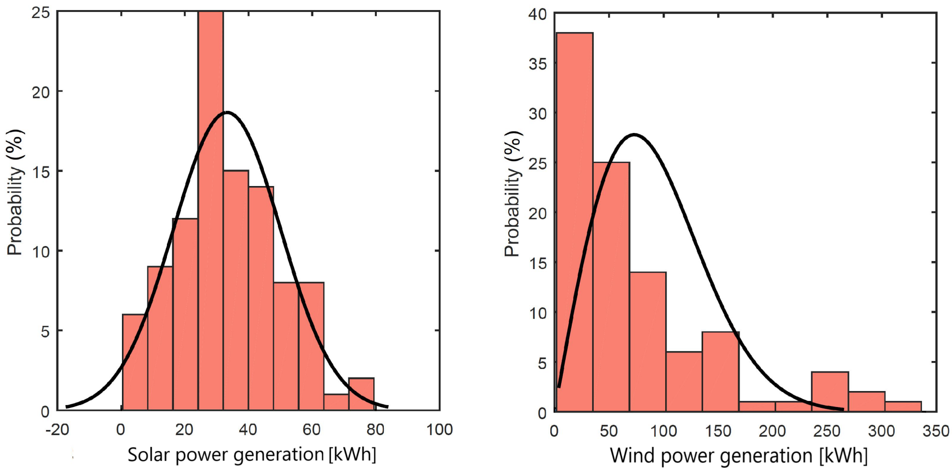


Figure 2.3: Generic wind and solar power production for an arbitrary day [88].

2.2.2 Balancing of power grids through interconnecting resources

Based on the growing share of renewable power penetration in the European grid, the need for balancing resources is expected to increase. Several technologies and measures can be used for balancing purposes, such as local storage, demand-management and cross-border exchange. The latter offers multiple possibilities for increasing the flexibility and balance of the power grid. Firstly, interconnections provide geographical dispersion for renewable power generation and thus have a smoothing effect on the overall VRES production [87]. Put another way, VRES production is constrained by the availability of the relevant resource and different areas may not encounter these resources (i.e. wind energy and solar irradiation) during the same periods of time. Hence, interconnections opens the possibility of exporting excess variable renewable power from one area to an area of deficit. Secondly, areas with high shares of variable renewable power generation can be balanced from areas with adjustable hydrothermal production sites. The large hydro reservoirs and production facilities in the Nordic region are often mentioned as an important contributor to the question of balance and storage of VRES in Continental Europe and the UK [32] [33] [27]. Thirdly, when the variable renewable power production in one area is higher than the demand, the excess production can be exported through interconnections rather than curtailed. All in all, interconnections provide compensating possibilities for variable renewable power.

Another important factor to consider is the fact that VRES is not spread uniformly over Europe. Instead, it tends to be concentrated in areas with high meteorological potential and supportive political environment [68]. Conventional power generation infrastructure, on the other hand, has normally been more aligned with load centers. Consequently, this calls for higher investments in transmission capabilities in order to balance the production and demand centres.

Furthermore, the production pattern from different RES technology is subjected to seasonal variance. VRES is based on intermittent production technologies meaning that they are considered independent of price, but varies with weather conditions [85]. Wind power is affected by air temperature as colder air is denser. Wind speeds are typically higher during winter due to the lower temperatures, which combined with the relative denser air, gives a greater production during winter than summer [99]. Regarding solar power the situation is quite the opposite, as solar irradiation is highest during summer. Moreover, solar plants only produces power during day while winds tend to be stronger during nights. Consequently, these two technologies become somewhat complementary [53] [79]. Hydropower production, on the other hand, is to large degree dependent on the variation in water inflow. The latter varies considerably throughout the year, where it is usually greatest during spring and autumn [85]. The power generation from many hydropower plants is however adjustable, which makes their production dependent on multiple factors. These may be regarding financial market aspects, future inflow to reservoirs, production from other plants etc. Together, these factors form what is known as "water-values", which relates the value of using water for production today to the expected value of using water in the future [60]. Figure 2.4 shows the weekly average hydro production in Norway seen over a period of 15 years [60].

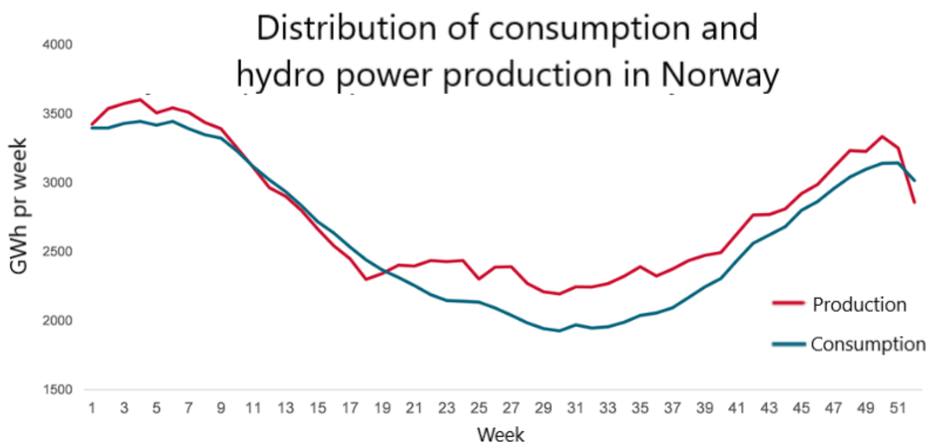


Figure 2.4: Weekly average of Norwegian hydropower production (red) and consumption (blue) from 2002 to 2017 [60].

2.2.3 Correlating implementation of VRES and interconnection capacity

The assessment of optimal cross-border exchange capacity with respect to future implementation of VRES has been a topic of broad interest in academic research, where e.g., the FLEX4RES project provides several studies related to this topic ([8] [4] [68] to mention a few). FLEX4RES is one of three "flagship projects" by the Nordic Energy Research [56], setting out to address how intensified interaction between coupled energy markets can facilitate the integration of RES in terms of stable, sustainable and cost-efficient operation.

Paper [8] aims to demonstrate the cost-optimal interconnection capacity in a decarbonized future European power system. The study suggests that the optimal installation between 2030 and 2050 is around four times the planned scale by 2030 found in "Ten Year Network Development Plan 2018" (TYNDP2018) published by ENTSO-E [17]. Paper [4] explores the correlation between interconnection capacity and implementation of VRES in Denmark following national action plans for carbon-neutrality by 2050. The study shows that Denmark shifts from a balanced electricity mix to a mix almost solely based on VRES in 2050. Accordingly, the optimal interconnection capacity following this is calculated to be more than three times the total capacity in 2030 found in TYNDP2018. Another study from 2013 [67] presents how the interconnection capacity, in a renewable European power system solely relying on variable resources (wind and solar), affects the need for balancing energy from conventional power plants. The study finds that roughly six times the installed European interconnection capacity as of 2012 level is sufficient to give a close-to-optimal utilization of VRES and thus minimizing the demand for balancing energy. All in all, there is a clear overall trend indicating that extensive implementation of VRES goes hand-in-hand with increased interconnection capacity.

2.2.4 Economic implications from implementation of VRES and interconnection capacity

There are several profound economic implications following increased penetration of VRES. As mentioned in Section 2.2.1, their low marginal costs might represent a game-changing factor in the electricity markets, as it is ranking VRES first in the merit order during price formation [68]. Hence, the supply curve, i.e. the sorted variable costs of all available power plants, is shifted whenever renewable energies contribute to balance the demand. Consequently, the intersection point between the demand and supply curve will be at lower price levels with the entry of VRES. This is called the merit order effect (see Figure 2.5). Various econometric studies document the reducing effect implementation of VRES has on power prices [89] [71] [51]. Following the logic of reduced average power prices is that of a shift towards greater consumer surplus and reduced producer surplus. Moreover, high share of VRES also has an interesting implication in the way that wholesale electricity prices get more strongly correlated to the power supply rather than demand. In other words, VRES creates an anti-correlation between power supply and power prices. On the other hand, the fluctuating nature of VRES also yields higher price volatility and greater frequency of very low-priced periods [61] [102] [70].

The change in price volatility brings the discussion over to the economic implications of increased interconnection capacity. The greater the price differences are between two areas, the more beneficial is the interconnecting resource between the areas due to bottleneck effects. In this context, a bottleneck refers to a transmission resource where the transfer capacity becomes a limiting factor for power exchange thus creating congestion and different price levels on each side of the resource. Hence, bottleneck-trading means trading of power between two price areas through the bottleneck. The area with a power surplus will evidently have lower prices than the area of power deficit. The bottleneck-trading therefore implies that power flows from the low price area to the high price area. The principle is right from society: *The commodity ought to move towards the consumers that express the highest demand and willingness to pay the highest price* [57] [84].

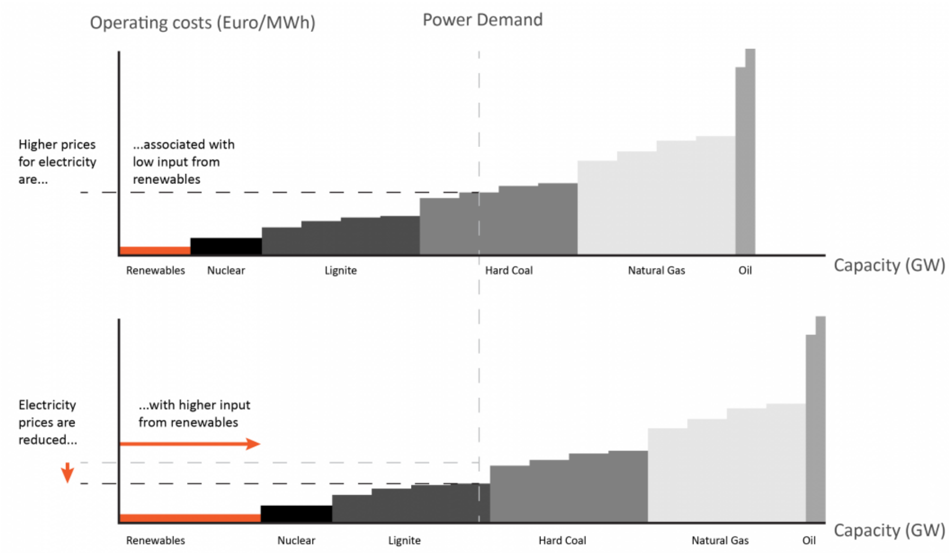


Figure 2.5: Merit order effect with the inclusion of more RES production to the production pool [13].

Nevertheless, the benefits from bottleneck-trading are asymmetrically distributed among connected regions and participating agents in the power market [8]. That is to say, the low-price region tends to have its power prices shifted upwards, which indicates a reduced consumer surplus and increased producer surplus. The opposite accounts for the high-price end of the interconnecting resource. Consequently, these asymmetric distributional effects demonstrates what can likely be a barrier for increased power exchange cooperation and shows the importance of proper policy design to meet these challenges.

Extensive interconnections between areas contribute to reduce the market effects of VRES as well as creating benefits for other generation technologies. The aforementioned anti-correlation between power prices and VRES production creates, from a VRES point-of-view, a large incentive for grid extensions. With grid extensions the potential burden of reduced revenues for conventional power plants, due to increased VRES penetration, is distributed more evenly across regions. Connecting more flexible power plants together also reduces the ramping of conventional plants, thus saving costs and emissions [37] [46]. Consequently, increased interconnection capacity can be advantageous for both conventional power plants and VRES - a rather unlike pair [68]. In total, a strengthening of cross-border trading installations bears multiple economic advantages.

2.3 Future development of power system

In the scenario study that is to come later in this thesis, most attention will be given three areas; UK, Norway and Sweden. In order to create a line of reasoning for the scenario build-up, some important elements with respect to the development of tomorrows power system are presented. Focal points will be changes in power plant park, power consumption and interconnection capacities.

2.3.1 Future power demand in the UK, Norway and Sweden

On general basis, increased electrification of heating, industry and transport contributes to increase the overall electric power demand [61] [15]. Moreover, in Norway and Sweden, new power demanding industries like data centers, battery manufacture and hydrogen production are believed to rise the power consumption further. In the UK a shift from conventional gas boilers to alternative electric heating technologies for residential heating will have a major impact on the national power demand [20]. On the other hand, increased electric energy efficiency driven by innovative solutions and improved technology limits the rapid growth in power consumption [43] [61].

2.3.2 Future power generation in UK, Norway and Sweden

The power plant park in all three countries will in the future be dominated by renewable generating facilities [16] [61] [20]. This is in line with the countries respective environmental policies and targets.

Net Zero Act

Over the last couple of years a lot of action plans have been presented of how various countries will reduce their carbon footprints in accordance to climate commitments. Amongst the most ambitious action plans is the "Net Zero Act" committing UK to a legally binding target of net zero carbon emissions by 2050. The net zero implies that any emissions must be balanced by schemes to offset these emissions, such as carbon capture-and-storage (CCS) and agricultural actions like planting trees. The act is considered to be the first case where a major economy pass laws to end its contribution to global warming [31]. As of 2019, UK has reduced their overall emissions by 42% compared to 1990 levels and to continue this decrease in emissions UK must, amongst other actions, add vast amounts of renewable energy into their electricity mix [104] [75].

The Swedish Energy Agreement

In Sweden it has been for the last decades an growing focus on green energy transition. In 2016 the Swedish government and opposing parties came to a conformity about the long-term Swedish energy policy. The agreement presents detailed plans for reaching 100% renewable power production by 2040, alongside having zero net emissions by 2045 [64]. Another important target of the agreement is to contribute to maintain a reliable Nordic power system with great security of supply. One of the main measures to obtain this is by further increase the transmission capacity between Sweden and its neighbouring countries [63].

2.3.3 Future interconnecting resources UK, Norway and Sweden

The overall trend seen nowadays in the European power grid is an increasing degree of meshing and interconnection [23]. This coincides with EU's interconnection plans encouraging to broad installation of resources for cross-border exchange through initiatives like the PCI (see below) [24]. In the case of the UK, the Network Options Assessment

(NOA) anticipates a growing volume of interconnecting resources between the UK and Europe [54]. NOA argues that interconnectors will help alleviate constraints in the British grid alongside stimulating and increasing the utilization of renewable power generation. The same logic accounts for the Nordic countries where there will be an extensive growth in interconnection capacity towards Europe [61].

PCI - Project of Common Interest

The European Union started in 2013 the Projects of Common Interest (PCI) initiative to promote investments in the grid that improve reliability and flexibility. The PCIs are key infrastructure projects aimed at strengthening the European energy market in order to promote EU's energy and climate policy: secure, affordable and sustainable energy for all citizens.

Chapter 3

Review of previous analyses

3.1 North Connect

3.1.1 General

The North Connect cable (NC) is a 1400 MW HVDC transmission resource planned to connect Norway and Scotland to facilitate direct exchange of electric power. It is intended to be built between Sima in Norway and Peterhead in Scotland with a total length of 665 km where approximately 440 km is on Norwegian side (see Figure 3.1). The connecting point to the Norwegian grid is in Simadalen, which makes it the first interconnection cable from bidding zone NO5 in Norway. The cable is on Norwegian side a collaboration between various parties; Lyse, Agder Energi, Hafslund E-CO and Vattenfall. These companies are all publicly owned. The overall estimated investment cost assumed to be 1.7 billion Euros is to be split equally between the Scottish and Norwegian parties [58]. NC is acknowledged as a project for energy infrastructure in the PCI initiative [83]. This implies that EU considers NC to improve market integration and contribute to reach EU's climate and energy goals [24].

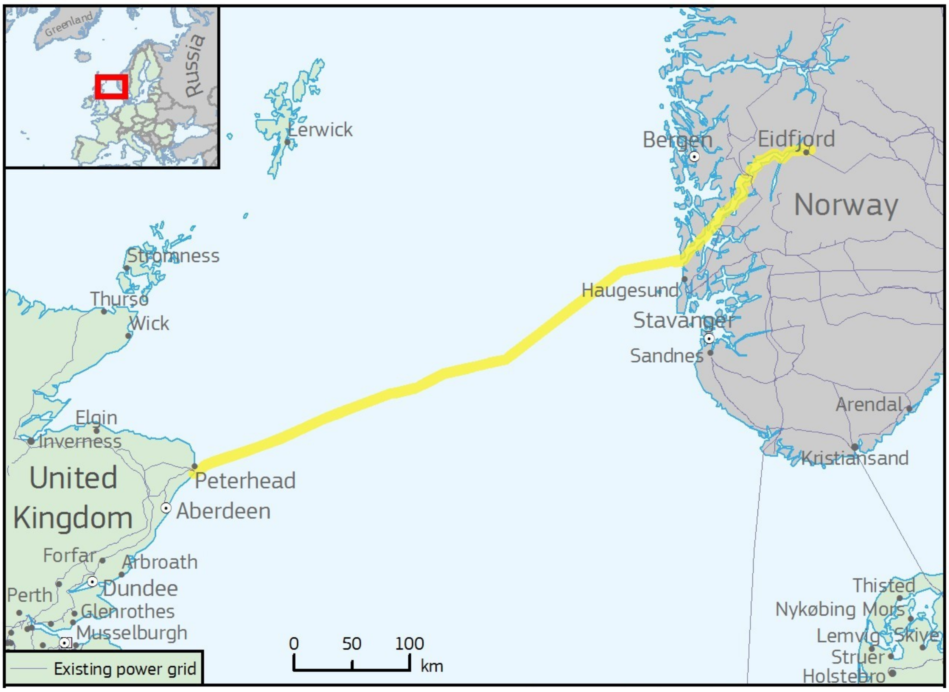


Figure 3.1: Map showing the geographical placement of the North Connect cable [25]

3.1.2 Assessment of North Connect done by The Norwegian Water Resources and Energy Directorate (NVE)

On behalf of the Norwegian Ministry of Petroleum and Energy (OED), NVE has been commissioned to assess the possible consequences NC has on natural resources, the energy system and the energy market [86]. In order to conduct this assessment, NVE has based its analysis on its long-term Power Market Analysis 2019-2040 [61]. The latter shows that British, as well as European, power systems are undergoing increased electrification, higher share of renewable power production and out-phasing of coal-fired power plants. A brief review of some of the most essential findings in the assessment is presented here.

Socioeconomic profitability

Overall, NVE found NC to be a socioeconomic profitable project. According to NVE, the congestion income, which is derived from the price differences between the connected zones is in itself not enough to make the project profitable. Furthermore, NC can be used by means of balancing the British power system through counter-trade, so-called SO/SO-trading. Counter-trading means, in short, that the transmission system operator (TSO) pays producers to either increase or decrease their production in order to balance the market. However, NVE has not accounted for this income post in their report. Nonetheless, their simulations show that Norwegian power prices will increase by 1-3 øre/kWh (1-3€/MWh with an exchange rate of 10NOK/1€) over the assumed lifespan of 40 years. This effect will be greatest during summer when the price normally tends to be low and water reservoirs are large. Such an increased valuation of the Norwegian power will to large degree benefit the power producers. This producer surplus outweighs the consumer deficit as NVE is assuming that Norway increases its power surplus in the future. The fact that most of the Norwegian power producers are publicly owned makes their increased revenues, in the long run, benefit the Norwegian state and local government authorities and in turn the power consumers [86].

Transit and distributional effects

Further, the NVE report shows that increased interconnection capacity to areas with major price fluctuations can lead to more transit flows (for an introduction to transit flows see Section 4.3). In particular, NVE states that the NC might give slightly increased imports on other existing interconnectors. Thus, implementing NC can lead to decreased export volumes on the interconnectors owned by Statnett, as the demand for power is kept constant through the whole period of analysis. Table 3.1 and Figure 3.2 show NVE's forecasted power exchange values and duration curves on NC and other interconnections from Norway. Moreover, the price level in Norway is assumed to be increasing with NC and hence the congestion income will drop due to both less traded volume and lower price difference. A consequence could possibly be increased network tariffs, which NVE estimates to be in the range of 0,4-0,5 øre/kWh [86]. As a matter of fact, NVE concludes that the overall congestion income will decrease as the income of NC does not compensate for the losses of Statnett.

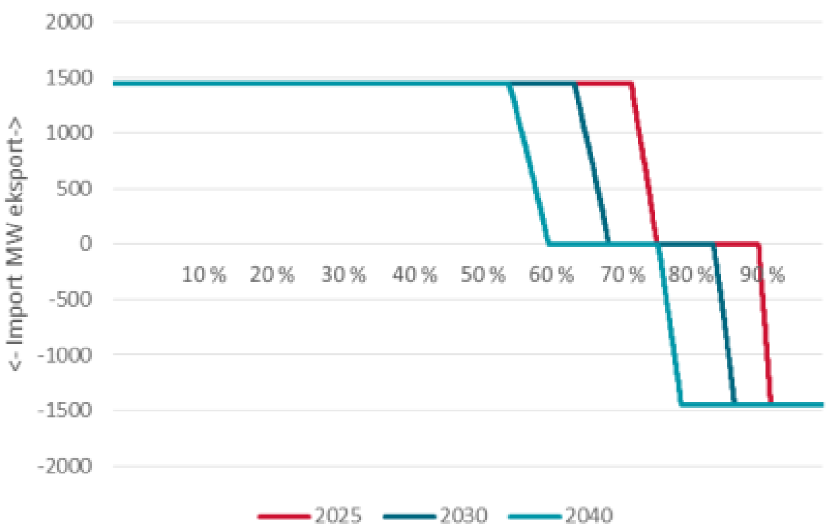


Figure 3.2: Duration curves for power flow for three model years presented by NVE [86]. Export is defined as power flow from Norway to UK.

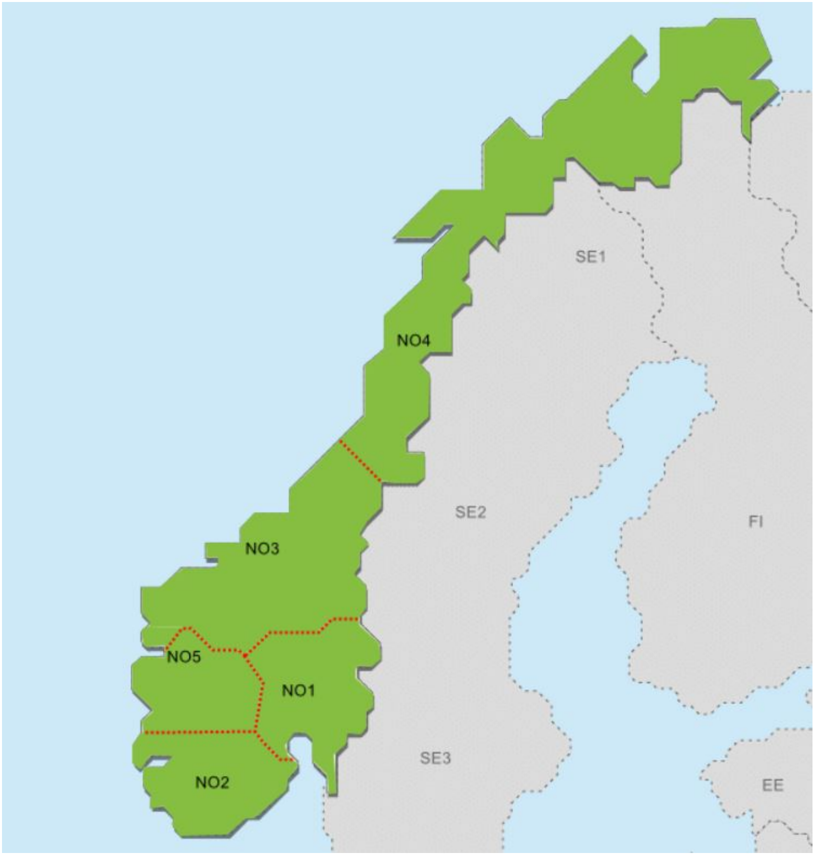


Figure 3.3: Sketch showing the bidding zones in the Norwegian power market [76].

Regarding the power flow in the Norwegian transmission grid, NVE finds major changes in the use of transmission resources when implementing NC. The reader is encouraged to keep an eye at Figure 3.3 while reading the rest of this paragraph. Typically, without NC, electric power is transferred from hydro-rich areas in the western (NO5), middle (NO3) and northern part (NO4) of Norway towards the overseas power links in the south (NO2) and the demand in eastern area (NO1). Following the implementation of NC is that the power flows from the north and middle parts of Norway are directed more towards NO5 and Sima. Consequently, the demand in NO1 has to be covered to larger degree by imports from Sweden alongside transmission from the Telemark area. The power flow towards NO2 decreases following the aforementioned reduction in export on existing interconnections. That being the case, the implementation of NC decreases multiple bottlenecks in the transmission system. Amongst these are the bottleneck between NO2 and NO5 alongside the bottleneck between NO1 and NO2. On the other hand, as the spot price is increasing more in the southern part of Norway than in the north, a strengthening of the bottleneck between NO1 and NO3 can be seen.

Table 3.1: Import and export on North Connect as well as existing interconnections presented by NVE [86].

Period	2025 [TWh]	2030 [TWh]	2040 [TWh]
Export North Connect	9,5	8,5	7,4
Import North Connect	1,0	1,7	2,7
Net export North Connect	8,4	6,8	4,7
Change export other connections	-5,5	-3,8	-5,3
Change import other connections	2,9	1,6	0,9

Uncertainties and Brexit

The European power system seen nowadays is undergoing extensive changes with common carbon mitigation initiative as the backdrop. Consequently, long-term analysis of the power market is subjected to uncertainty relating to power production pools and demand, alteration of the power grid and the emergence and development of power markets.

There are congestions in the British transmission network. How these congestions are handled does, to large degree, impact the environmental footprint and potential long-term savings of carbon emission of the NC. Bottlenecks between Scotland and England might prevent green hydropower from reaching England displacing thermal power plants.

Furthermore, the politically controversial Brexit has thrown further uncertainty on the expected development of the power grid and market. An important factor is whether or not the UK will continue to be a part of EU's common internal energy market. It is considered likely that Brexit will introduce less efficient trading arrangements with interconnecting countries. Despite these uncertainties, the fundamental differences in generating facilities between Norway and the UK will continue to apply [86]. That is to say, irrespective of Brexit, the variance in power generating pools between the countries will make trading still being beneficial for both parts.

3.1.3 Assessment of North Connect done by project group North Connect KS

NVE did not have the mandate of assessing the carbon mitigation effect following the implementation of NC. That being the case, as the potential climate effect of NC is one of the key arguments to invest in this transmission resource. Hence, the project group behind NC has presented their estimations of carbon savings. The conclusion to this work was that the annual overall emission reduction will be of around 2 Mtons CO_2, which according to the report corresponds to the annual emissions from one million passenger vehicles or around 4% of the annual Norwegian greenhouse gas emissions [59].

To perform this climate calculation the project group is focusing on two major factors. Firstly, a power system in Scotland with high penetration of wind power must be balanced by some kind of adjustable power generation. That is to say, during periods with less wind the power demand has to be met through production facilities. The project group, on their part, is simplifying the balancing power to be derived from gas-fueled thermal plants in Scotland. Consequently, the interconnection capability that NC gives can make hydropower from Norway partially displace this gas power. Secondly, the project group is pointing out that the UK is experiencing an increasing share of wind power in their electricity mix. Hence, there are periods where the wind power production is greater than what the grid capacity can utilize, and due to this, wind power plants has to be shut down periodically. NC gives in such a case the opportunity for Scotland to export green energy to Norway, which then either can be consumed or used to pump water to hydropower reservoirs. As of 2019, the potential "savings" of this wind power were around 2 TWh [66].

The mathematical approach to this climate accounting is based on NVE's aforementioned report regarding calculated import/export values between Norway and interconnecting countries (Table 3.1). Next, average values over the three model years presented are found for each row. A CO_2 intensity of 500 kg/MWh is set for gas-fueled power plants. Ultimately, this number is multiplied with the average values to obtain the emissions presented in Figure 3.2.

Table 3.2: Overall changes in CO_2 emissions according to North Connect KS [59]

Period 2025-2040	Change in CO_2 emissions [Mton CO_2/year]
Export to UK	-4,2
Import from UK	-1,0
Export existing connections	2,3
Import existing connections	0,8
Total	-2,1

3.2 Analysis report on interconnections to Germany and Great Britain by Statnett

Before beginning the on-going construction of two new interconnections towards Germany and England, the Norwegian TSO, Statnett, published in 2012 an analysis report regarding the effects this would have for the Norwegian power grid [77]. Some of the results will be presented here as they are considered also to be relevant for the NC cable.

Increased interconnection capacity from Norway will have a considerable impact on the power flow between Norway and Sweden. The exports from Norway to Sweden will decrease and conversely do imports to Norway increase. This is due to the fact that some Swedish power plants will partially cover the export on Norwegian interconnections and that the Swedish power surplus is expected to increase.

Greater power exchange capacity raises the production of flexible hydro plants during times of export. This gives increased power flow on the Norwegian domestic grid towards the landing point of the cables. Hence, there might be periods of congestion and bottlenecks in the grid at the expense of the foreign power exchange. Accordingly, there is a need for reinforcements in the power grid, especially in the southern part of Norway. Moreover, the increased exchange capacity amplifies the already existing flow pattern towards Continental Europe. The Nordic power system is dominated by hydropower, which maintains a relatively steady price level throughout the day. Hence, the exchange pattern, where Norway imports power during night, as power prices on the Continental Europe are low, and exports power during day, is strengthened with two new interconnectors.

Chapter 4

Power Flow Tracing

Power flow tracing (PFT) is a method that gives the possibility of correlating power flowing in a line to specific generators or loads. It was originally conceived by means of realising equitable transmission service pricing, but has for the last two decades received significant attention from agents in the power system research community in improving PFT models and algorithms. This comes as a consequence of the range of applications when using PFT, from aspects related to environmental studies and greenhouse gas emissions to diverse areas of modern power system design and operation [3].

One of the many applications for power flow tracing is the study of CO_2 emission apportioning. By use of this methodology, calculations on how consumer demand relates to CO_2 emissions can be done. Power flow tracing provides in such a way a useful tool that can be used for carbon allocation purposes. In combination with rational carbon obligations and policies related to electricity exchange among regions, this could contribute to demand-driven stimulus for carbon mitigation. Consequently, the application of power flow tracing supports closer cooperation between supply and consumer side for common carbon recognition and mitigation.

In line with the ever-increasing carbon mitigation initiative, more and more research are being done related to environmental and socioeconomic footprint analysis [97]. Consequently, various models have been developed to reflect how these emissions flows from producer to consumer. Amongst these models one can find, e.g., the concepts of graph theory-based power flow tracing [45], statistical analysis [7] and value chain analysis [97]. The latter has originally been conceived as a basis of life cycle analysis with a historical perspective. Value chain models are based on huge databases containing information about production and consumption of goods, as well as trade of goods between areas. Thus, performing such analysis has tended to be a time-consuming process with time frames not stretching further than the present state-of-the-art. However, more recent times have shown that the value chain approach can, in combination with simulations of the future global goods market, be a powerful tool to provide forward-looking insight into how policy impacts carbon flows [97]. Ultimately, by simulating the power grid and using those results as the input database of the value chain analysis one obtain a power flow tracing method that mathematically differs from the more conventional approaches found in [6] [47] [1].

4.1 Power flow tracing algorithm

Power flow tracing can be performed on a system where either some kind of power flow analysis has been run, or by using historical measured values. This is crucial whereas the input parameters of power tracing algorithms are usually the generation and load at buses, as well as the line flows and their corresponding losses. In this thesis, the EMPS model (as described in Chapter 5) will provide the power balances necessary to perform PFT. Figure 4.1 shows the work flow when using power flow tracing:

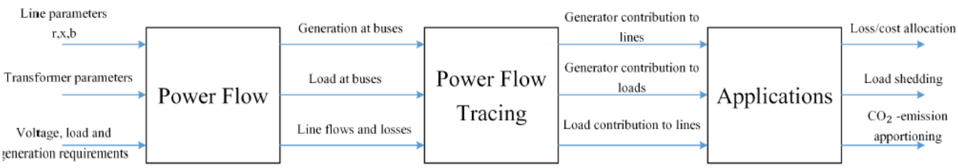


Figure 4.1: Conceptual diagram showing PFT in correlation with Power Flow analysis and some of it applications [3].

4.1.1 Multi-regional input-output analysis

Multi-regional input-output (MRIO) analysis is a top-down approach that can be used to estimate consumption-based emissions at area-level [96] [49]. The model uses input-output tables where such tables typically represents production and demand for given goods in a given area. These tables are combined with trade data between areas to allocate the flow of goods. Hence, by knowing the amount of production/consumption, alongside the trade of goods, the model provides a good basis for calculating flow of carbon emissions from a consumer-based perspective.

Conceptually, MRIO analysis is derived from the quantitative input-output model found in economics. The latter model is credited to W. Leontief, who he earned the Nobel Prize in Economics for his study of interdependencies between regional economies. For the last decade, MRIO analysis and databases have extensively been applied to calculate environmental footprints of nations (see e.g., [34], [72] and [98]). Nonetheless, as constructing these databases is a very time-consuming process and depends on the availability of national statistics, footprint calculations are usually only available with a time lag of a couple of years or more. On the other hand, some first estimations of projections using MRIO has been conducted and opened up the possibility of assessing policy impacts in terms of future environmental footprints [96].

The basic mathematical model underlying the MRIO model is the linear equation seen in Equation 4.1. For a derivation of this equation, the reader is encouraged to see [72].

$$X = AX + Y \tag{4.1}$$

where:

- X is the output matrix showing the extent to which the goods in an arbitrary area are being consumed or exported from the area
- Y is the final demand of all goods in the areas
- A is a square matrix that represents the intermediate demand relations between areas

Equation 4.1 is solved for X. By settling the CO_2 emission intensities for the various goods, the total emissions can be calculated. This is shown in equation 4.2.

$$\begin{aligned} e_{tot} &= efX \\ e_{tot} &= ef(I-A)^{-1}Y \end{aligned} \tag{4.2}$$

where:

- e_{tot} is the total CO_2 emissions vector
- ef is the vector containing the CO_2 intensities of the different goods

However, there are a couple of drawbacks with this model. The accuracy of the calculations depends on various factors, including the resolution of the input/output tables. Tables missing values must be handled, often through interpolation. Secondly, constructing these tables, that is to say building a database with information about global goods production, consumption and trade, is a very time consuming process and source of error.

4.1.2 Method concretisation of tracing algorithm

The power flow tracing algorithm used in this thesis was developed by J. Clauss [11], during his time as a Ph.D. student at NTNU. The algorithm itself is based upon the concept of a multi-regional input-output approach (MRIO) as explained in Section 4.1.1. Essentially, this implies an iterative process with a downstream source-to-sink approach. To do so, Clauss presents a generic methodology divided into several steps to investigate consumption in terms of its source of origin.

The PFT algorithm sets out to evaluate the hourly average CO_2 intensity in a meshed power grid. The structure of the dataset being used in the algorithm is better presented in a list:

- The power grid is divided into various nodes, where each node can represent a bidding zone (BZ) in the real-world power market or other geographical areas that is found appropriate. As was presented in Chapter 3, Norway, e.g., is divided into five BZs.
- Each node is delegated with different electricity generating technologies (EGT).
- Areas that are not a part of the interconnected network presented in Chapter 5 are omitted from the study. This is done to reduce complexity of calculation and because such outlying nodes are considered to have little impact on the nodes of interest.

- Power exchange between nodes are represented in the same way as EGTs. Hence one can make a general structure of the overall dataset where every bidding zone is represented in the same way. This is shown in Figure 4.2.

$$BZ_j = \begin{bmatrix} P_{BZ_j,EGT_1}(t_1) & & \cdots & & P_{BZ_j,EGT_m}(t_1) \\ & \ddots & \vdots & \iddots & \\ \vdots & & P_{BZ_j,EGT_i}(t_g) & & \vdots \\ & \iddots & \vdots & \ddots & \\ P_{BZ_j,EGT_1}(t_{8760}) & & \cdots & & P_{BZ_j,EGT_m}(t_{8760}) \end{bmatrix}$$

where
- i is the *"index of EGTs"* ranging from 1 to m
- j is the *"index of a specific BZ"*
- g is the *"hour of the year"* ranging from 1 to 8760 (or 8784)

Figure 4.2: Matrix showing contribution of each EGT for all hours of the year [12].

Calculation methodology

The following will be a brief presentation of the calculation methodology of the power flow tracing algorithm. For a more extensive explanation of the logic behind, the reader is encouraged to read [11]. The terminology bidding zone (BZ) and node will be used interchangeably, but refers both to a given area.

The PFT algorithm is iterating through the abovementioned dataset one hour at a time. The iteration itself is pretty straight forward. A matrix for each bidding zone is created, containing power generated from each EGT and imports from neighbouring bidding zones (see 4.3). To normalize the values into per units, the production from each technology and imports are divided by the sum of production and imports in each respective bidding zone. This is done with the normalization matrix seen in Figure 4.4. Multiplying these two matrices gives the power production and power imports per unit in a bidding zone as shown in Equation 4.3.

$$T(t) = \begin{bmatrix} P_{BZ_1,EGT_1}(t) & & \cdots & & P_{BZ_n,EGT_1}(t) \\ & \ddots & & \iddots & \\ \vdots & & P_{BZ_j,EGT_i}(t) & & \vdots \\ & \iddots & & \ddots & \\ P_{BZ_1,EGT_m}(t) & & \cdots & & P_{BZ_n,EGT_m}(t) \end{bmatrix}$$

where
- i is the *"index of EGTs"* ranging from 1 to m
- j is the *"index of BZs"* ranging from 1 to n

Figure 4.3: Matrix showing power from each bidding zone for each hour of the year [12]

$$N(t)=\begin{bmatrix} \frac{1}{\sum_i P_{BZ_1,EGT_i}}(t) & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\sum_i P_{BZj,EGT_i}}(t) & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\sum_i P_{BZ_n,EGT_i}}(t) \end{bmatrix}$$

where

- i is the *"index of EGTs"* ranging from 1 to m
- j is the *"index of a specific BZ"* ranging from 1 to n

Figure 4.4: Normalization matrix with the inverted sum of production in respective BZ on the diagonal [12]

$$P(t) = T(t)N(t) = \begin{bmatrix} P_{EGT} \\ P_{import} \end{bmatrix} \tag{4.3}$$

At this point, the logic from Section 4.1.1 about MRIO comes into play. In this case, the sum of imports and power production in an arbitrary BZ should be consumed or exported from the BZ in question. This complies with the well-known fact that there has to be balance at all times between production and consumption in a power system [62] [67]. Overall, one gets the following formula:

$$M(t) = P_{EGT}(t) + M(t) * P_{import}(t) \tag{4.4}$$

Solving for matrix M gives:

$$M_{(i,j)}(t) = P_{EGT}(t) * (I - P_{import}(t))^{-1} \tag{4.5}$$

Hence, $M_{(i,j)}$ gives the share of power from the various generating facilities (EGT_i) in each bidding zone (BZ_i) for each time step. That is to say, both share of production from internal EGTs and share of production from external EGTs are accounted for. The electricity mix in each BZ is assumed to be homogeneous, making the aforementioned shares of power evenly distributed for the entire bidding zone. Given the fact that production and power exchange are dynamic variables subjected to time variations, a new matrix will be formed every new time step. Furthermore, the output matrix $M_{(i,j)}$ can be combined with the CO_2 intensities related to the respective EGTs (ef_{EGT}). An overall summation will give the CO_2 intensity of the electricity mix in a BZ_j:

$$e_j(t) = \sum_{i=1}^{m} ef_{EGT_i} * M_{(i,j)}(t) \tag{4.6}$$

Here, the index of EGTs ranges from $i = 1$ to $i = m$ and index j relates to a specific bidding zone.

Finally, a quantitative measure of total CO_2 emissions in a bidding zone can be calculated as the product between power consumption and CO_2 intensity:

$$Em_{BZ}(t) = E_{BZ}(t) * e_j(t) \tag{4.7}$$

where Em_{BZ} is the overall CO_2 emissions for a bidding zone at a given hour and E_{BZ} is the overall energy consumption of the same bidding zone.

4.2 Simplified power flow tracing

On simple few-nodal systems, the use of power flow tracing algorithms can sometimes be somewhat exaggerated. On these systems, a more simple and intuitive approach, hereby called quasi-PFT, can be utilized. This approach takes into account export and import values from a node and adjusts the overall electricity mix depending on domestic production and power trades. The methodology will only briefly be introduced in this section, while a more fulfilling example can be found in Section 7.3.5.

The structure of calculation for studying how power flows from node A, through node B and ends up in node C (path: A - B - C) is as follows:

1. Find domestic power production, power export and import for node B
2. Calculate the overall electricity mix in node B by summing the domestic power production with net exports to other nodes
3. Extract the import value coming from node A and find the how much this value contributes to the overall electricity mix in node B
4. Use the share found in the previous point and multiply with node B's export to node C. The amount of power stemming from node A ending up in node C is hereby calculated.

Several important assumptions that have been done in this calculation. First and foremost, the imports to node B from node A is assumed to "mix evenly" with the rest of the electricity mix, thus creating a homogeneous power pool. This is not carved in stone in real-life power systems, as they are subjected to physical laws implying that the imports might just as well be consumed right away at the point of interconnection as elsewhere. Second of all, every power exchange between node B and other nodes happens simultaneously. That is to say, net export from node B to an arbitrary node cannot be accounted for before all other power exchanges with node B is taken into account. Hence, the methodology does not take into account that the exports from node A to node B might happen after all the export from node B to node C. That being the case would have resulted in zero power flowing from node A to node C, transiting through node B.

The vigilant reader might have noticed the similarities between this methodology and the one used in the MRIO methodology from Section 4.1.1. That is for a good reason, as the procedure presented here builds on the same logic as used in the MRIO methodology. The difference lies first and foremost in the electricity mix used at the ends of the calculated path. In this section, the electricity mix in the starting point is assumed to be purely from node A, while it might in fact be a sum of domestic power production and power exchange with node X, Y and Z. The same accounts for node C. Hence, the actual power produced in node A, which is consumed in node C, might differ from the what is found using the procedure above. The MRIO methodology, however, does take into account all power exchanges for each time-step, and gives accordingly a more nuanced picture of the overall power flow.

4.3 Unscheduled power flows

As the power grid of today is highly meshed and strongly interconnected, multiple paths exist from a source (generator) to a sink (load). These paths are utilized depending on network parameters and laws of electricity [52]. From a market management point-of-view, a power transaction is typically detailed with path description and amount of power transferred. The TSOs ensures that the path is physically and electrically valid for the aforementioned transaction. In practice, however, some portion of any scheduled flow may traverse other transmission resources than those indicated in the transaction. These digressions, as seen in Figure 4.5, are called "unscheduled flows" (USFs) and are a result of the inconsistency between the physical dynamics of the power system and financial principles of the power market [80]. The USFs can, in power system simulations, be difficult to detect as they demand high resolution in terms of grid components and transmission lines.

Experience has shown that a significant fraction of transmission charges might come from USFs. During summer 2008, e.g., the uplift costs shared by market participants around Lake Erie in the New York electricity market was estimated to be 96 million dollars [10]. Unscheduled power flows can be divided into two groups depending on their place of consumption; so-called loop and transit flows [26]. Both concepts are illustrated in Figure 4.6. As seen from the figure, loop flows indicates power flows stemming from scheduled flows within an area. Transit flows, on the other hand, indicates that the power has travelled through external bidding zones before reaching the consumer.

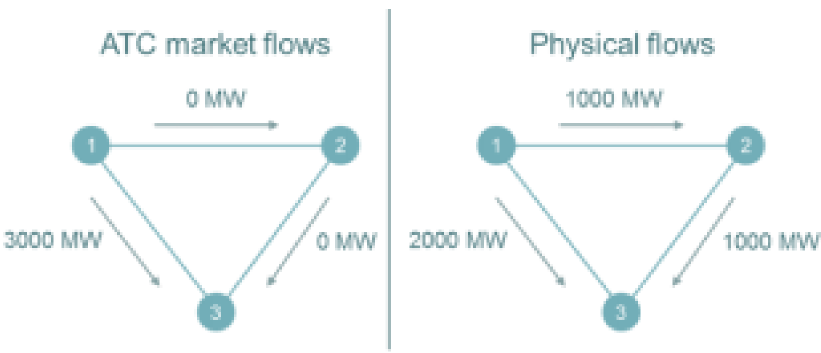


Figure 4.5: Illustration of available transfer capacity and physical flows

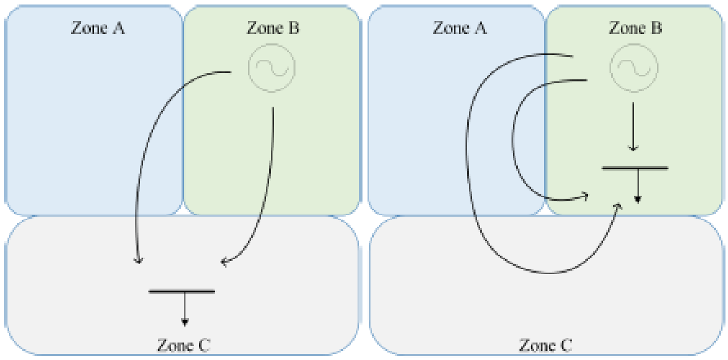


Figure 4.6: Transit flows (left) and loop flows (right)

The USFs are significantly reducing the amount of cross-zonal capacities. Doing so have a negative impact on the functioning of the power market and cross-border trade. Moreover, USFs may cause adverse effects by overloading lines, potentially leading to compromised security and reliability, as well as incurring uncompensated losses for third parties [81]. If transmission capacities in a region are scarce, unscheduled flows may give rise to congestion issues. It follows that this could lead to increased CO_2 emissions - as less, possibly renewable, power can be transferred in the given area. Allocating the unscheduled flows with origin in other regions through PFT can give a more nuanced congestion management and thereby fair pricing and more efficient use of transmission capacity [69].

As USFs are not accounted for in the stage of market coupling, TSOs need to handle these flows separately. This can be done in multiple ways:

- Topology measures and use of Phase Shifting Transformers. This approach directly influence the physical flows in the grid, but as such measures normally are not widely coordinated between TSOs, this might solely move the problem elsewhere in the grid.

- Redispatching might be costly for the host bidding zone and does not necessarily give an optimal solution seen from a system perspective.

- Unilateral reduction in available transfer capacity on host interconnectors might reduce system costs, but at the detriment of efficient trade and market integration.

- Implementation of flow based market coupling to handle cross border trade and internal bottlenecks. This methodology was inaugurated in May 2015 in Central Western Europe's day-ahead market and is believed to be integrated in other market zones as well [5].

4.4 Carbon emission flow and power flow tracing

Delegation of responsibility and quantification of carbon emissions is essential in a world where the focal point is low-carbon development [44]. Historically, when calculating the CO_2 intensity of domestic grid mix, the state-of-the-art has been to consider CO_2 intensities of imports as fixed [11]. Moreover, emissions have been attributed to generating facilities. This accounts typically for statistical analysis [7] and life cycle analysis [95]. Nowadays, however, a trend shift is taking place, pointing out that consumers, rather than producers, should be held accountable for the emissions of CO_2. After all, production and thereby carbon emissions are dynamic responses to the real-time demand in the power system. For illustrative purposes, to obtain a consumer-based perspective, one can imagine the carbon emissions from generating facilities to be acting as a virtual flow alongside the corresponding power flow. Hence, carbon emissions can be accumulated at the consumer end and thereby quantified [45].

In addition to allocate CO_2 emissions from a consumer-based perspective, the proposed PFT methodology quantifies the hourly CO_2 intensities of the electricity mixes. This facilitates the study of how domestic CO_2 intensity varies with different time scopes, i.e. from intra-day to inter-seasons. The forthcoming section studies some of the applications such an insight opens up for. For a more in-depth introduction to how CO_2 intensities can be used to estimate the CO_2 emissions related to consumption, the reader is encouraged to read [29].

4.5 CO_2 intensity of consumed electricity mix and its applications

With sustainable development and carbon mitigation as backdrop, it is useful to obtain knowledge about the carbon intensity in the consumed electricity mix. Such a knowledge opens up for a range of applications that contributes to the optimization of "green energy" consumption. Two of the most prominent concepts are:

- Vehicle2Grid - Implementation of electric vehicles (EV) into the power grid as a remote energy storage
- Renewable energy optimization in buildings - Dynamic usage of energy in buildings depending on CO_2 intensity in the grid

Vehicle2Grid

Nowadays, the western world is experiencing a trend shift in terms of electrification of the transport sector. A report from the World Economic Forum shows that by 2040 more than half of the cars sold worldwide annually will be electrical [103]. Moreover, the share of EVs is estimated to be more than 70% in Europe and 50% in China. This opens up for a range of possibilities. EVs can be considered a decentralized energy source providing storage capacity and controllable electricity demand when fully integrated with grid edge technologies. Smart charging opens up for a more flexible energy system, improving security and reliability [103]. That is to say, the electric car fleet can contribute to peak shaving and valley filling, thus optimizing peak-capacity investments. The possibility of storing energy in the EV makes it into a potential buffer in the grid, that can be set to "maximize the power consumption" during periods of high renewable penetration in the electricity mix. To do so, knowledge about the typical intra-day development of CO_2 intensity is essential.

Renewable energy optimization in buildings

According to the International Energy Agency, buildings were responsible for 28% of global energy-related CO_2 emissions in 2018, corresponding in absolute terms to an all-time high [40]. With the energy flexibility found in buildings, there is a large potential for load shifting and emission reductions. There are two ways to obtain a more sustainable power usage; increase the energy efficiency of buildings and decarbonize the energy supplied to buildings [12]. The CO_2 intensity can be used as an indicator for the fraction of renewable in the electricity mix, and hence create a control signal for buildings. In other words, energy intense processes in buildings can be shifted in a way that they consume the most energy during periods with high renewable penetration [11].

Drawbacks by use of CO_2 intensity as a signal for power consumption

Despite the promising applications of CO_2 intensity with regards to sustainable power usage, the proposed methods do however not come without limitations. That is to say, if the power usage in EVs and buildings is based upon the CO_2 intensity of the electricity mix, one might see major shifts in pattern of consumption. Consequently, if the number of participating agents is significant, an imbalance will appear between real-life and predicted power demand. Hence, balancing power would be required. Balancing services do typically have relatively high CO_2 emission intensities, as they are often based on fossil-fueled generation, thus overall creating sub-optimal CO_2 emissions [2] [11].

Chapter 5

EMPS Model

5.1 General

The EMPS (EFI's Multi-area Power-market Simulator) is a market simulator used for forecasting and planning in the electricity market. The model was developed in the 1970s for purposes of optimizing scheduling of Norwegian hydropower. As the European power market has grown more and more complex throughout the years, the EMPS model is now often used in terms of optimization of hydropower in hydrothermal power systems [73]. The model is capable of simulating most of the European power system and provides insight to price formation, energy transmission and environmental effects. Several agents in the Scandinavian power market are using the EMPS, including TSOs, power producers and consultant companies.

The objective of the model is to minimize expected system cost for the power system of interest. Put another way, the model sets out to maximize total economic surplus. Hence, the solution proposed from the EMPS will coincide with the outcome in an ideal and well-functioning electricity market (see [74] for discussion). The numerical calculation in the model forms two parts. Firstly, stochastic dynamic programming is used to set up an optimal strategy for hydropower generation. Thereafter, linear programming is used to simulate the whole system week by week over a given time period consisting of a range of different climate years. Furthermore, the constraints regarding the physics of the power grid is handled through a transport model. For the simulations conducted, this implies that power generation and consumption is allocated to nodes and that power can be transferred through the grid wherever there is a free capacity. For a more in-depth description of the EMPS model the reader is encouraged to read [100] and [101].

5.2 Model elements

The model used in this thesis consists of the following:

- 34 countries with 44 nodes
- Total of 98 transmission lines
- 787 thermal power plants of 17 different types
- 43 nodes with hydropower
- 39 nodes with solar generation
- 43 nodes with wind generation

Norway and its interconnecting countries have the highest resolution in terms of nodes. This can be seen from Figure 5.1 where Norway is divided into five areas, whereas Sweden has four, Great Britain has three and Denmark has two. The nodes in the three Nordic countries corresponds to the respective bidding zones found from the real-life power market (see [57]). Transmission lines in red indicate onshore connections, while the ones in blue are offshore connections. Appendix 9.3.1 shows all nodes in the EMPS model. Countries outside the simulated network, for instance Russia and parts of Eastern Europe, are omitted from the study. In other words, their impact on the European power flows are neglected.

As seen from Figure 5.1, Great Britain is divided into three areas. The reader should be made aware that these areas are denoted as UK-N, UK-M and UK-S. This is somewhat misleading as they only cover Great Britain, while the UK in real-life also includes Northern Ireland (NI). From the map, however, NI is seen to be an independent node. The notation seen in Figure 5.1 will, nonetheless, be used in the rest of this thesis.

Due to the complexity of a real power system, there are naturally many essential model elements to take into account when operating with this software. Amongst these are the following:

- Hydropower
  - Detailed model described with different attributes like storable/non-storable inflow, capacity and waterways for overflow and bypass-mechanism.
- Other generation
  - Thermal plants: Capacity, cost of fuel and cost of CO_2.
  - RES: Zero costs and generation based on historical hydrological factors.
- Transmission
  - Capacity, loss and availability specified for each transmission line between areas.
- Consumption
  - Demand specified by levels ranging from annual time horizon to hourly prices within a week. Demand also affected by weather conditions.

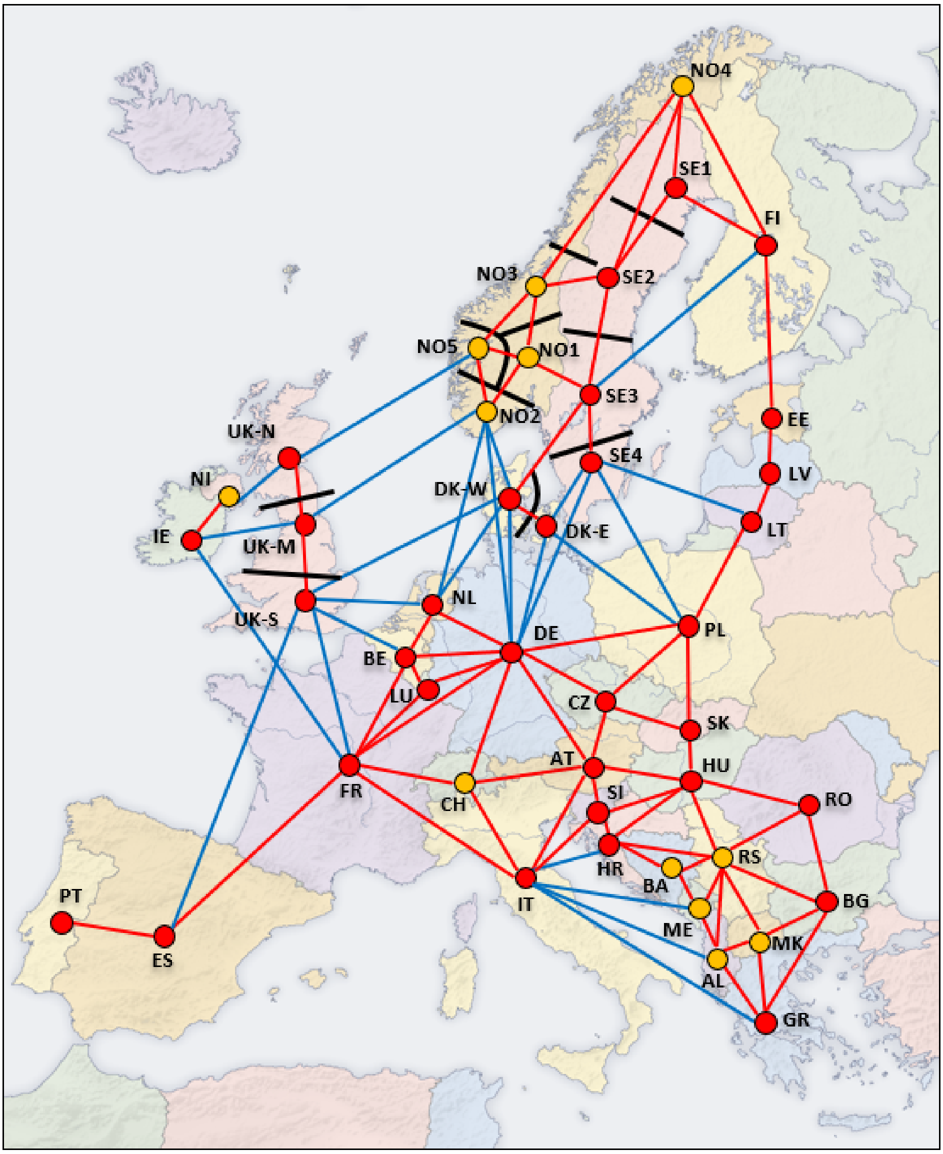


Figure 5.1: Map showing the nodes and their interconnections used in the EMPS model.

5.3 Hydropower - strategic calculation and simulation

The optimization of hydropower utilization is divided into two parts; first a strategic calculation and then simulation. There are several stochastic variables in the model due to the implications the weather has on hydropower generation (in terms of inflow, temperature that affects demand and alternative renewable power generation from wind and solar facilities). Since water reservoirs can either be utilized in the present or stored for future use, the problem is considered to be dynamic. To simplify, the energy production for different climate variables are aggregated into one stochastic variable called water-value. Hence these water-values represent the marginal value of stored water with respect to future possibilities for income. They are, in general, strongly correlated with neighbouring thermal power production as imports represent the alternative to domestic hydro production. Figure 5.2 shows iso-curves for water-values for reservoir levels and weeks.

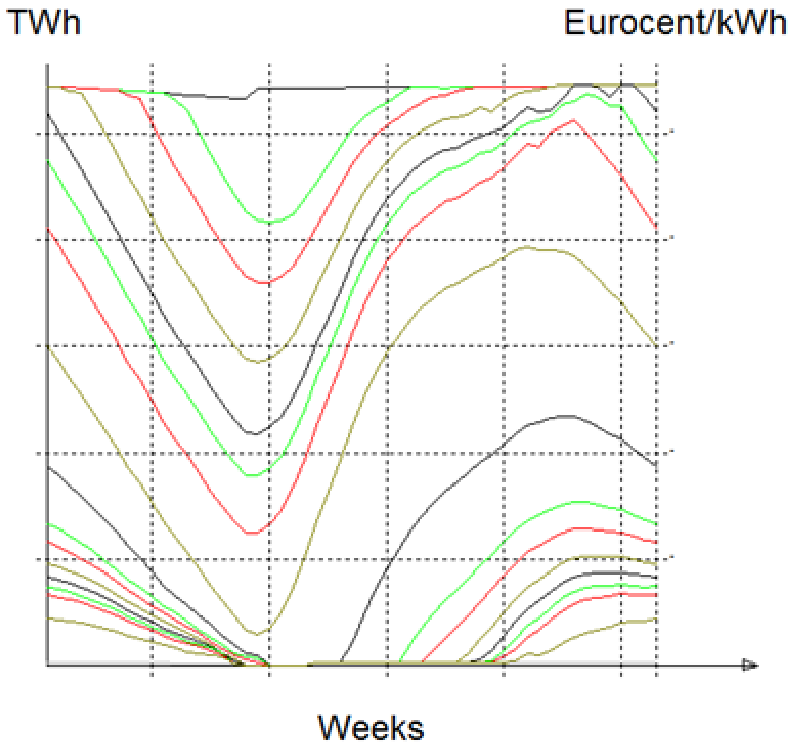


Figure 5.2: Iso-curves (constant value curves) for given reservoir levels and weeks [101].

To further simplify the optimization problem, all reservoirs in one area are aggregated into one equivalent reservoir. See [100] for further information about the strategy calculation.

When the model is undergoing week-by-week simulation, the water-values are treated as marginal costs for hydropower. The simulation is done for each scenario, i.e. each weather year. The whole interconnected system is simulated, including all model elements described in the list above. During the optimization, an iterative process is performed to minimize system costs. For the reader, that is not fully updated on power market analysis, a quite simplified way to illustrate this is that the optimization procedure is trying to find the most beneficial market equilibrium. In Figure 5.3 the intersecting point between supply and demand shows the market equilibrium for a generic area with generic marginal costs for various generating facilities. Altogether, the EMPS maximizes the total economic surplus for each weather year. Average values of all parameters such as production, transmission, power prices etc. is ultimately calculated to yield the final EMPS simulation results. Ultimately, in order to handle situations where nodal production exceeds consumption and energy exchange through interconnections at a given time step, each node is equipped with a so-called sink. The fact that the sink at some point can be used to "consume" excess power can give simulation results where power production is seen to be slightly greater than demand. Oppositely, if there is a net power deficit in a node at a given time step, the power price could potentially increase drastically. Some demand will therefore be dropped to reestablish power balance.

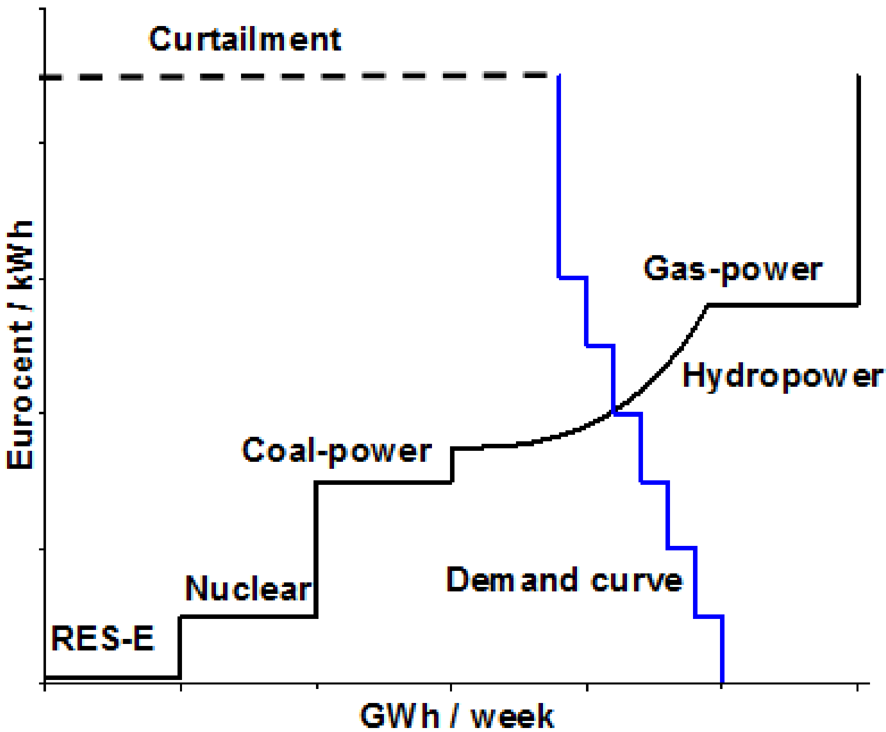


Figure 5.3: Generic market equilibrium. The blue line demonstrates the demand curve, while the black line is the offer curve. Notice how the greatest (dotted) demand is limited. This curtailment reflects the maximum available generation capacity plus import capacity for the area.

5.3.1 Simulated time span

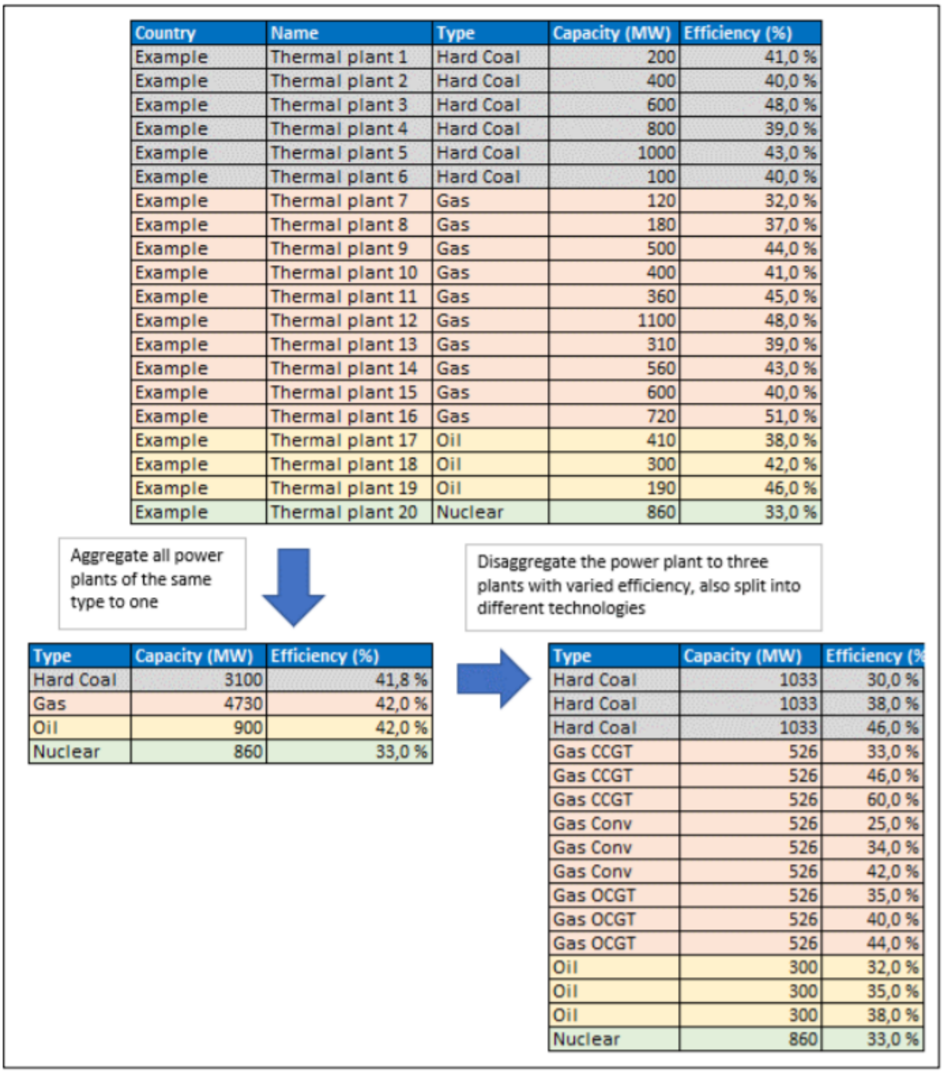
The energy system is simulated utilizing information of 75 different weather years. The weather datasets are provided by NOAA [55]. It consists of 61 consecutive years of wind data and 22 years of solar data. In order to fill up the total of 75 years, various wind/solar datasets are reused. Each simulated year will therefore yield different production patterns for each node. This gives a sufficient representation of possible weather variations and good enough difference for values regarding inflow, wind and solar [90]. Finally, the average hourly production value of each node for the whole time span is found. This yields a resulting matrix showing each generator in each node and their corresponding hourly production throughout the year.

5.4 Energy system description

The EMPS model consists of a various range of power plant types, shown in Table 5.1. As there exist hundreds of individual power plants in Europe, all power plants are categorized into groups depending on their corresponding technology. The capacity of each group is then partitioned to their respective countries/nodes. Figure 5.4 shows this workflow. To represent a changing European power plant fleet, where more efficient technologies replace the old, every power plant technology is separated into three different sections depending on their maturity. That is to say, if the plant is old, standard or modern. Accordingly, their efficiencies vary thereafter.

Table 5.1: Different generation technologies used in the EMPS model.

Category	Fuel Type	Power plant	Remarks
Thermal	Coal	Hard Coal	
		Lignite	
	Gas	Gas - Conventional	Steam plants
		Gas - OCGT	Open-cycle gas turbine
		Gas- CCGT	Combined-cycle gas turbine
		Gas - CCS	Carbon capture and storage
	Oil	Oil	
	Nuclear	Nuclear	
Renewable	Wind	Wind	
	Solar	Solar	
	Hydro	Hydro	Reservoir and run-of-river
	Biomass	Biomass	
	Other RES	Other RES	e.g. tidal, wave and geothermal
Others	Others	Others	e.g. hydrogen and methanol
CHP	Coal	CHP - Coal	CHP based on coal
	Coal	CHP - Coal	CHP based on coal
	Gas	CHP - Gas	CHP based on gas
	Oil	CHP - Oil	CHP based on oil
	RES	CHP - RES	CHP based on biomass
	Diverse	CHP - Diverse	CHP based on other fuel types



Country	Name	Type	Capacity (MW)	Efficiency (%)
Example	Thermal plant 1	Hard Coal	200	41,0 %
Example	Thermal plant 2	Hard Coal	400	40,0 %
Example	Thermal plant 3	Hard Coal	600	48,0 %
Example	Thermal plant 4	Hard Coal	800	39,0 %
Example	Thermal plant 5	Hard Coal	1000	43,0 %
Example	Thermal plant 6	Hard Coal	100	40,0 %
Example	Thermal plant 7	Gas	120	32,0 %
Example	Thermal plant 8	Gas	180	37,0 %
Example	Thermal plant 9	Gas	500	44,0 %
Example	Thermal plant 10	Gas	400	41,0 %
Example	Thermal plant 11	Gas	360	45,0 %
Example	Thermal plant 12	Gas	1100	48,0 %
Example	Thermal plant 13	Gas	310	39,0 %
Example	Thermal plant 14	Gas	560	43,0 %
Example	Thermal plant 15	Gas	600	40,0 %
Example	Thermal plant 16	Gas	720	51,0 %
Example	Thermal plant 17	Oil	410	38,0 %
Example	Thermal plant 18	Oil	300	42,0 %
Example	Thermal plant 19	Oil	190	46,0 %
Example	Thermal plant 20	Nuclear	860	33,0 %

Type	Capacity (MW)	Efficiency (%)
Hard Coal	3100	41,8 %
Gas	4730	42,0 %
Oil	900	42,0 %
Nuclear	860	33,0 %

Type	Capacity (MW)	Efficiency (%
Hard Coal	1033	30,0 %
Hard Coal	1033	38,0 %
Hard Coal	1033	46,0 %
Gas CCGT	526	33,0 %
Gas CCGT	526	46,0 %
Gas CCGT	526	60,0 %
Gas Conv	526	25,0 %
Gas Conv	526	34,0 %
Gas Conv	526	42,0 %
Gas OCGT	526	35,0 %
Gas OCGT	526	40,0 %
Gas OCGT	526	44,0 %
Oil	300	32,0 %
Oil	300	35,0 %
Oil	300	38,0 %
Nuclear	860	33,0 %

Figure 5.4: Aggregation and disaggregation for an arbitrary area [90].

5.4.1 CO_2 intensities for power plants

In order to calculate the CO_2 emissions from each and every generator, the CO_2 emission intensities for the different generation technologies has to be decided upon. The simulations only consider point-emissions, that is to say, emissions related to the production of electric power. Table 5.2 sums up the different intensities for modern-type generating plants. Thermal power production based upon non-fossil sources are considered to have zero emission intensity. This accounts for instance to bio and nuclear plants. Furthermore, each generator plant has different efficiency depending on its maturity. The specific intensity of a generation plant is therefore dependent both on its fuel combustion and maturity. To calculate the specific carbon intensity Equation 5.1 is used. Generation facilities based upon renewable sources, like hydro, wind and solar power, are assumed to have a CO_2 intensity of 0 kg/MWh.

$$U_{CO_2}^{Specific} = \frac{U_{CO_2}^{Theoretical}}{\eta} \tag{5.1}$$

Table 5.2: CO_2 intensities for power plants with modern-type generation technologies [94].

Fuel Type	Efficiency η [%]	Theoretical intensity [kgCO_2/MWh]	Specific intensity [kgCO_2/MWh]
Hard Coal	50,8	370	728
Lignite	47,2	500	1059
Gas Oil	35,3	300	850
Heavy Oil	44,3	350	790
Gas	60,9	200	328

Out-phasing of old technology and increase of efficiency

In line with the development of more efficient technologies, the power system is in constant transformation. The changes in the European power plant fleet is accounted for in two ways in this thesis. The first step is by phasing out old generating technologies. Conventional plants, for instance, are thus gradually substituted by more modern plant technology. Secondly, the decommissioning of old power plants are taken into account. This reflects how newer, more profitable, plants with better efficiencies outperforms plants that are reaching their end-of-lifetime. Table 5.3 shows the distribution of maturity and plant technology for year 2040.

Table 5.3: Development of power plant park with respect to age and technology improvements. Exemplified with gas-fueled technologies [90]

Maturity	**Old**	**Moderate**	**Modern**
2040	0%	15%	85%
Technology	**Gas-Conv**	**Gas-OCGT**	**Gas-CCGT**
2040	5%	25%	70%

Installed capacity and generated energy

The operation of generating facilities depends on the power plant type. Plant types with low marginal costs (baseload power plants like nuclear) and/or plants with multiple constraints (e.g., CHP) can possibly generate at all times. The same accounts for renewable power plants (wind, solar and run-of-river), as long as their climatic time series indicates possibilities for generation and power prices are greater than zero. The annual energy such plants can produce is given as an input to the EMPS mode and thus such form exogenous variables to the model. Power plants based on fossil fuel, like coal, gas and oil, are modelled with production capacity. Thus, these plants form endogenous variables to the model and are the only flexible production facilities in the system. This has important implications for the simulated results, which will be handled in Chapter "Discussion" 8). Table 5.4 shows the different plant types grouped by their input value.

Table 5.4: Input values and operation dependencies of different generating technologies

Input value	Power plant type	Operational dependencies
Installed capacity	Hard Coal, Lignite, Gas, Oil Hydro (reservoir)	Fuel price, CO_2 price
Generated energy	Nuclear, Biomass Combined Heat-and-Power, Others	Fuel price, CO_2 price
Time series	Wind, Solar, Hydro (run-of-river)	Directly based on input

5.4.2 Simulation tasks performed by the EMPS model

The EMPS model offers insight into a wide range of aspects in the power market. Among these are the following:

- Long term operational scheduling of hydropower
- Investment analysis
- Maintenance planning
- Forecasting of electricity prices
- Utilization of transmission lines and cables
- Calculation of energy and power balances
- Calculation of CO_2 emissions from power generation

From the list above, it is the four latter points that are of most interest in this thesis. These will be further investigated in Chapter 7 "Results".

5.4.3 Implementation of power flow tracing algorithm

The implementation of the power flow algorithm used in this thesis is a module created through several steps. The NTNU Ph.D. student J. Clauss presented the overall methodology in 2018 [12]. One year later, two following Ph.D. students, K. Thorvaldsen and D. Pinel expanded the algorithm and made it more universal. Ultimately, for the purpose of this thesis, the PFT algorithm has yet another time been re-implemented to make it function well with the EMPS model.

Figure 5.5 shows a simple flow chart of the algorithm procedure and computational process. Due to the length of the code and the multiple script interactions, the complete implementation of the power flow tracing algorithm is provided in Appendix 9.3.1. As seen from Figure 5.5, the input dataset necessary for the calculations is firstly read from the EMPS simulations and reformatted. Then an interative process begins, where both the nodal electricity mix with respect to plant technologies and contribution of power from other nodes is calculated. These calculations are then combined with data about consumption and CO_2 intensities in power plants for each iterated time step. Lastly, the output data regarding power distributions between all nodes in the system and their CO_2 emissions for each time step is saved to files. Overall, the algorithm forms an external module to the EMPS. The module itself is not publicly released and is only meant for NTNU in-house simulations.

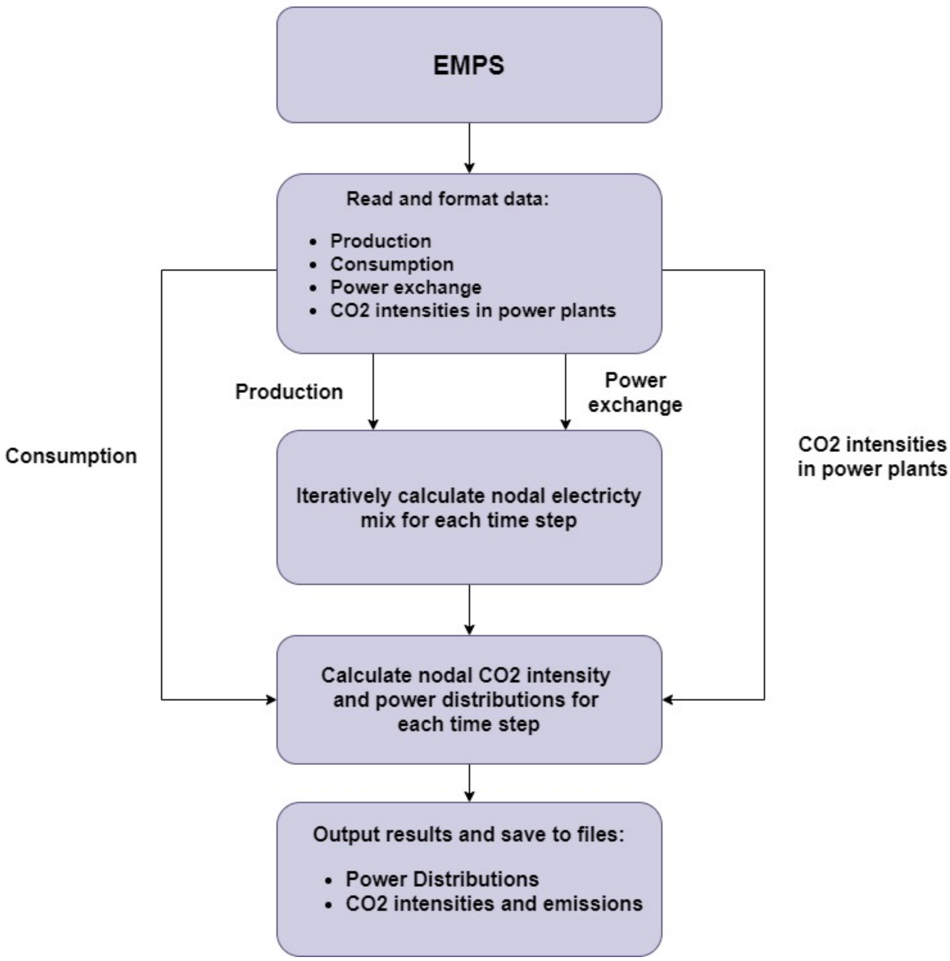


Figure 5.5: Simple flow chart showing the implementation of the power flow tracing algorithm.

Chapter 6

Scenario simulations

6.1 Scenario building

6.1.1 General

This thesis sets out to simulate the electricity market in most of Europe for the year 2040, subjected to two different scenarios. Both scenarios will be simulated twice, with and without a cable from NO5 to UK-N (see Figure 5.1). The cable will hereby be denoted as "the UK-N cable" and has a transfer capacity of 1 400 MW. Table 6.1 shows the four simulations. Keep in mind that the change in transfer capacity between Norway and the UK only is due to the alteration of the UK-N cable. The cable from NO3 to UK-M remains connected in all simulations.

Various European and national action plans lay the foundation for the simulated power market done in the EMPS model. In the following sections, the two scenarios will be further presented. Section 6.1.3 gives a brief overview of the first scenario building, as it is being thoroughly explained a Master's Thesis from 2019 by M. Ulvensøen [90]. The second scenario is presented in Section 6.1.4.

Table 6.1: Overview performed simulations

Simulation	Year	Scenario	Grid Topology
2040_CP_withoutCable	2040	Current Policy	Without UK-N cable
2040_CP_withCable	2040	Current Policy	With UK-N cable
2040_WindSolar_withoutCable	2040	Wind&Solar	Without UK-N cable
2040_WindSolar_withCable	2040	Wind&Solar	With UK-N cable

6.1.2 Input data

Simulation done with the EMPS requires a wide range of various input data; information about power plants, interconnection capacities, demand, costs etc. The simulation is done with a fairly long time horizon (2040) and thus it is favorable with datasets that satisfy a high level of detail for the given year. The "EU Reference Scenario 2016" (REF2016) [22] was chosen to lay the foundation for the scenario building. The latter is one of EU's key analysis tools in terms of energy, transport and climate action. It provides an extensive framework that gives a consistent approach for projecting long-term economic, energy and climate outlook within Europe.

The data regarding hydro reservoirs and run-of-river plants are taken from models used in SUSPLAN. The latter is a project within CORDIS in EU and is intended to stimulate innovative services and stimulate growth across Europe [82].

The input of transmission resources to the EMPS model is based on data from "Ten Year Network Development Plan 2016" (TYNDP2016) [18]. This report is issued by the ENTSO-E, a network of 42 TSO's from across Europe. TYNDP2016 is also used as a basis to model the none-member countries of EU.

In 2040 - Wind&Solar the data concerning the UK has been retrieved from "FES 2019 - Future Energy Scenario" (FES2019) [20], which was issued by the ESO of Great Britain, National Grid. In the case of Norway and Sweden, reports from the "Power Market Analysis 2019-2040" (NVE) [61] and "Scenarier över Sveriges energisystem 2018" [16] are being utilized.

FES 2019 - Future Energy Scenario 2019

The "FES 2019 - Future Energy Scenario" (FES2019) [20] is an annual report issued by the British ESO National Grid. The report describes four different scenario trajectories for the development of the British power market towards 2050, see Figure 6.1. The two scenarios, "Two Degrees" and "Community Renewables", assumes an offensive domestic green-shift policy. Consequently, they are also the only two scenarios which fulfill the former British target of 80% reduction of emissions compared to 1990-levels. The main difference between the two FES2019 scenarios is the degree of decentralization of power generation.

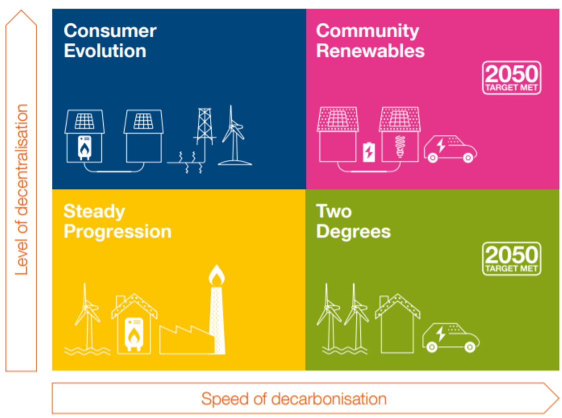


Figure 6.1: Matrix showing the four scenarios presented in FES2019 [20].

6.1.3 Scenario 2040 - Current policy

This scenario is supposed to reflect the European power system in 2040, as forecasted by the REF2016. Some of the submitted national action plans have been extensively altered since REF2016 was published. Hence, the REF2016 can be considered to be somewhat conservative in terms of future development of sustainable power generation. The notation for this scenario study, 2040 - Current Policy and 2040 - CP, will be used interchangeably throughout the thesis.

Power generation

Table 6.2 shows the share of renewable and conventional thermal power generation for UK and Sweden according to REF2016. The values for Norway are retrieved from the TYNDP2016. Hydro, wind, solar and other renewable facilities like tidal are named "Renewable", while the rest is considered as thermal generating facilities.

Table 6.2: Share of installed renewable and thermal power capacity in 2040 in absolute and relative terms for Norway, UK and Sweden according to REF2016.

Technology	UK [GW]	UK [%]	NO [GW]	NO [%]	SE [GW]	SE [%]	Total [GW]
Renewable	47	34	41	99	26	58	134
Thermal	77	66	0,6	1	17	42	146
Total	124	100	42	100	43	100	280

Transmission capacities

Table 6.3 highlights the simulated interconnection capacities in Norway and the UK, including the UK-N cable.

Table 6.3: Simulated interconnection capacity in Norway and UK in 2040, including the UK-N cable

Connections from Norway	Capacity	Connections from the UK	Capacity
Sweden	4495MW	France	12600 MW
Denmark	1640MW	Ireland	4400 MW
Germany	3500MW	Northern Ireland	1000 MW
Netherlands	700MW	Netherlands	1000 MW
Finland	50MW	Belgium	1000 MW
United Kingdom	2800MW	Spain	2000 MW
		Norway	2800 MW

6.1.4 Scenario 2040 - Wind&Solar

Various ambitious action plans has the last couple of years been established by Nordic and Western-European countries in order to fulfill their climate obligations. This scenario sets out to reflect an intensified facilitation of renewable power and interconnection between nodes. As discussed in Section 2.2.3, strengthened and expanded interconnections between countries allows for further implementation of unregulated power generation. This scenario will first and foremost alter the power generation and consumption for Norway, Sweden and the UK.

Power generation and consumption

To emulate the increased renewable power generation, new set points for their maximum power generation are set in the EMPS model (see section 5.4.1). Table 6.4 summarizes the planned renewable power generation in 2040 as well as the forecasted demand according to the these action plans.

Table 6.4: Renewable power generation and overall demand forecasts in year 2040 for both scenarios. All values in TWh.

	Norway			Sweden		
Technology	Current Policy	Wind&Solar	Change	Current Policy	Wind&Solar	Change
Hydro	136	151	11%	71	66	-7%
Wind - onshore	5	28	460%	14	43	207%
Wind - offshore	3	10	233%	9	20	122%
Solar	0	7	-	0	7	-
Biomass	0	1	-	23	14	-39%
Demand	127	159	25%	152	156	3%

Table 6.4: Renewable power generation and overall demand forecasts in year 2040 for both scenarios. All values in TWh.

	United Kingdom		
Technology	Current Policy	Wind&Solar	Change
Hydro	6	7	17%
Wind - onshore	60	53	-12%
Wind - offshore	40	178	345%
Solar	9	37	311%
Biomass	65	18	-72%
Demand	395	422	7%

Transmission capacities

For the simulations without the UK-N cable, the interconnection capacity between UK-S and France is increased with 1 400 MW. Table 6.5 shows the alteration in exchange capacity.

Table 6.5: Interconnection capacity between UK, Norway and France with and without the UK-N cable.

Nodes	With UK-N cable	Without UK-N cable
UK - FR	12600 MW	14000 MW
UK - NO	2800 MW	1400 MW

Chapter 7

Analysis and Results

7.1 Overview Results

The results from the EMPS simulation and the power flow tracing are presented in multiple sections. Table 8.1 presents the structure of the results.

Table 7.1: Structure of Chapter "Analysis and Results"

Section	Results
7.2	Power production and consumption
7.3	Power exchange between nodes
7.4	CO_2 emissions
7.5	Power flow tracing
7.6	Power prices

7.2 Power production and consumption

As presented in Chapter 6, the two scenarios are based upon two different estimations for the development of the power system for the simulated year of 2040. This has a major impact on production and consumption patterns calculated in the EMPS.

Figures 7.1 and 7.2 show the changes in the production mix for the simulated nodes with and without the UK-N cable. It is seen that there is an asymmetry between whether thermal power plants reduce or increase their production. In 2040 - CP, Germany and Poland stands out with a raise in coal-fired plants yielding greater CO_2 emissions. Spain, France, Italy and the UK are amongst the countries reducing their thermal (mainly gas) production the most. In 2040 - Wind&Solar, however, one can see that the UK-N cable lowers the production in gas-fueled plants in multiple countries, while only a few increases their thermal production. Appendix 9.3.1 gives a more detailed data set over the production mixes.

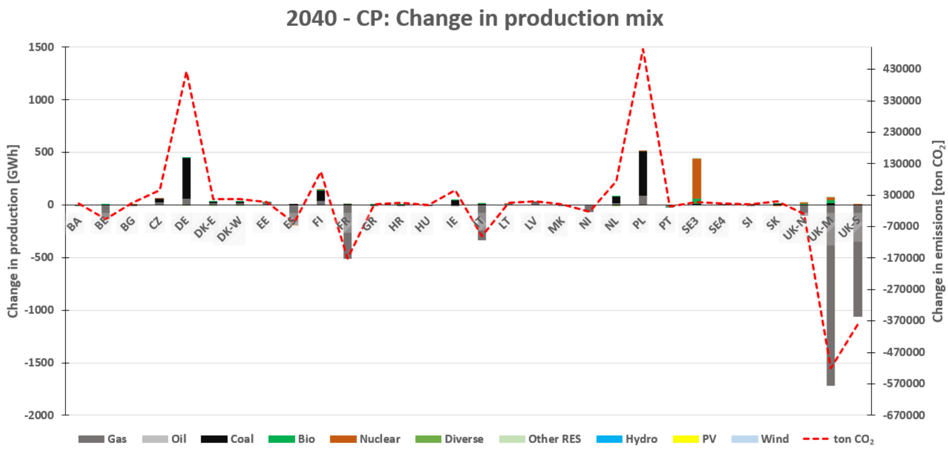


Figure 7.1: 2040 - Current Policy: Change in power production mix and CO_2 emissions. Nodes that have an overall change in CO_2 emissions of less than 1000 tons are omitted from the figure.

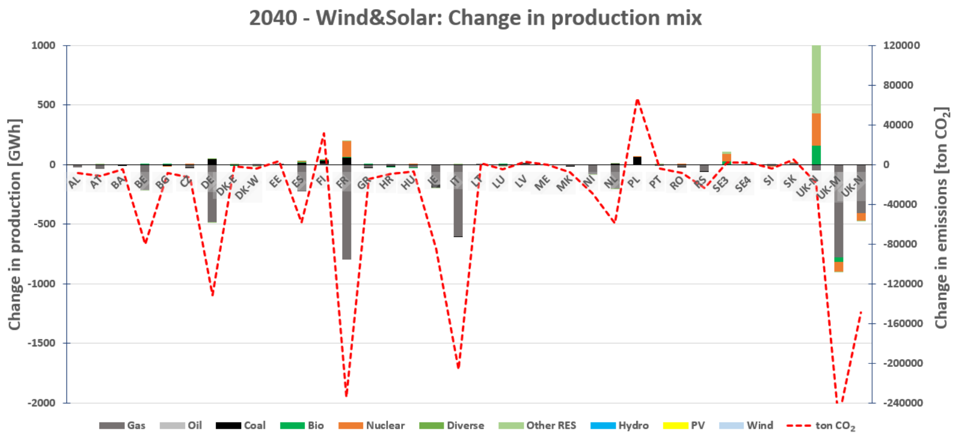


Figure 7.2: 2040 - Wind&Solar: Change in power production mix and CO_2 emissions. Nodes that have an overall change in CO_2 emissions of less than 1000 tons are omitted from the figure.

To get the figures more into perspective, Table 7.2 shows the production mix with the UK-N cable for both scenarios. As seen from the table, gas-fired power plants reduce the most in both scenarios, whilst coal-fired plants increase the most. The relative change, however, is not as great as one first might get the impression of from the two previous figures. The observant reader will notice from the previous figures and Table 7.2 that the overall production drops in both scenarios following the UK-N cable. This will be further discussed in Section 8.1.

Table 7.2: Overall production data for the whole simulated system including percentage change from simulation without the UK-N cable

Technology	2040 - Current Policy Production [TWh]	Change	2040 - Wind&Solar Production [TWh]	Change
Nuclear	740	0,06%	666	0,05%
Bio	284	0,03%	227	0,08%
Gas	408	-0,9%	359	-1,2%
Coal	439	0,3%	416	0,04%
Oil	1	0,2%	1	0,06%
Diverse	17	0%	17	0%
Other RES	126	0%	166	0,34%
Hydro	628	0%	639	0%
Solar	293	0%	335	0%
Wind	705	0%	894	0%
Total	3641	-0,06%	3721	-0,08%

Table 7.3 shows the production and consumption data for the connecting ends of the UK-N cable; NO5 and UK-N.

Table 7.3: Seasonal production, consumption and surplus in NO5 and UK-N when implementing the UK-N cable. Bio and nuclear account as thermal power plants. Summer is defined as 1st of May to 31st of October.

2040 - Current Policy				
Nodes	NO5 [TWh] Winter	NO5 [TWh] Summer	UK-N [TWh] Winter	UK-N [TWh] Summer
RES Generation	11	14,7	24	16,7
Thermal Generation	0	0	6,9	6,1
Total Generation	11	14,7	30,9	22,8
Total Consumption	11,6	7,6	21,8	18
Total Surplus	-0,6	7,1	9,1	4,8
2040 - Wind&Solar				
Nodes	NO5 [TWh] Winter	NO5 [TWh] Summer	UK-N [TWh] Winter	UK-N [TWh] Summer
RES Generation	15	17,5	57,6	42,6
Thermal Generation	0	0	3,7	3,8
Total Generation	15	17,5	61,3	46,4
Total Consumption	14,6	9,5	23,4	19,3
Total Surplus	0,4	8	37,9	27,1

Table 7.3 shows that the net power surplus in NO5 during summer will be of 7,1 TWh

in 2040 - CP and 8 TWh in 2040 - Wind&Solar. The net power deficit seen during winter in NO5 in 2040 - CP is turned to slight surplus in 2040 - Wind&Solar. In the case of UK-N, the net surplus is more than four times greater in the 2040 - WindSolar scenario than in 2040 - CP.

Figure 7.3 presents the hydro production in Norway, the VRES production in Sweden, alongside the power surplus in both countries when having implemented the UK-N cable in 2040 - Wind&Solar. In order to produce more intuitive graphs, there are used moving averages (MA) of 168 hours (1-week). The corresponding figure representing 2040 - CP is found in Appendix 9.3.1.

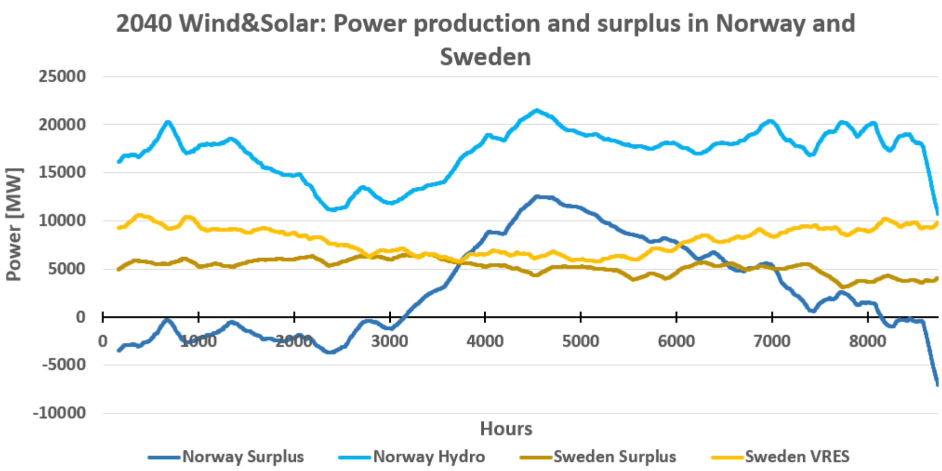


Figure 7.3: 2040 - Wind&Solar: Norwegian hydro production, Swedish wind and solar production alongside power surplus in both countries for scenario 2040 - Wind&Solar, including the UK-N cable.

From Figure 7.3 one can easily see that the Norwegian power surplus is greatest during summer. This is due to the fact that consumption is relatively low, while hydro production is relatively high. Oppositely, there is a power deficit in Norway during winter. In the case of Sweden, its power surplus is dropping slightly during summer. As described in Chapter 6, a significant portion of total power production in Sweden in 2040 - Wind&Solar comes from VRES. This is reflected in the graph where one can see that the VRES production nearly halves from winter to summer reducing domestic power surplus.

7.3 Power exchange

7.3.1 2040 - Current Policy

Figure 7.4 shows how the power exchange between Norway and other countries changes with and without the UK-N cable. The changes in import and export of UK-N are also highlighted. Appendix 9.3.1 gives a more detailed representation of the data.

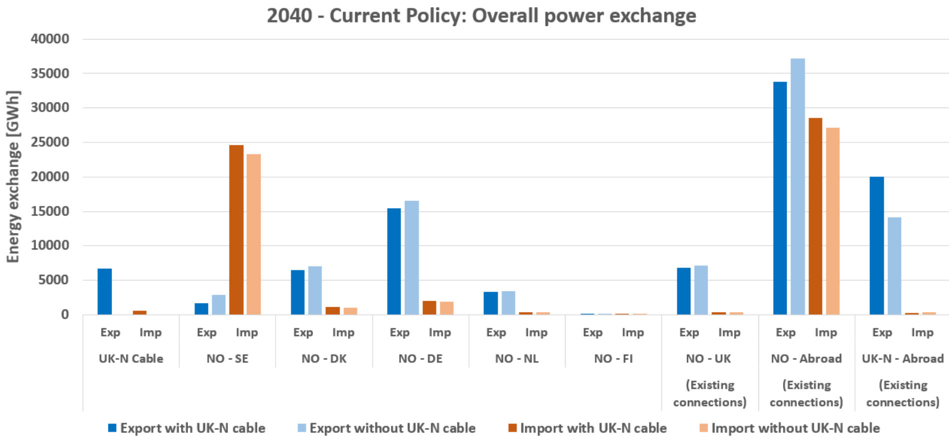


Figure 7.4: 2040 - Current Policy: Overview of export and import between Norway and neighbouring countries and power exchange between node UK-N and its neighbouring nodes. Export on the UK-N cable is defined to be from NO5 to UK-N. See Appendix 9.3.1 for exact values.

As seen from Figure 7.4 the UK-N cable is mainly used for export from Norway to node UK-N. The energy flow from NO5 to UK-N is seen to be more than ten times greater than the flow from UK-N to NO5, and thus do Norwegian export account for more than 90% of the total power exchange between these two nodes. Furthermore, it can be seen that Norway reduces its exports to all other countries following the implementation of the UK-N cable. Conversely, Norway increases the imports from neighbouring countries with the UK-N cable. This effect is, relatively, strongest between Norway and Sweden where the export from Norway is reduced with 40%. The effect on power exchange with Sweden will be studied more in detail later on. Additionally, power exchange through the cable between NO3 and UK-M reduces due to the UK-N cable. Germany can be seen to make up the biggest importer of Norwegian hydropower. Consequently, the reduction of exported Norwegian energy to Germany is, in absolute terms, the greatest. When studying node UK-N, the figure shows that the imports to UK-N remain of somewhat the same order of magnitude. The exports, however, are increased with 42% following the UK-N cable.

Correlation power exchange through the UK-N cable and power production UK-N and NO5

Figure 7.5 shows the correlation between wind and solar power production in UK-N, hydro production in NO5 and the power exchange through the UK-N cable. Note that the graphs are represented by means of 24h moving averages in order to give a less oscillating and better illustration of the power flow and production. The figure shows that the hydropower production is on average the greatest during summer. Oppositely, the VRES production in UK-N decreases during summer, which corresponds to the wind power production pattern described in Section 2.2.2.

From Table 7.3 it was shown that NO5 is experiencing a net power surplus during summer. Consequently, the red line representing NO5 - UK-N power exchange, indicates that the UK-N cable is solely utilized for exporting surplus hydropower from Norway to UK-N during summer. Conversely, one can see that the direction of power exchange varies slightly during the winter, where a share of the surplus renewable energy from UK-N sometimes is exported to NO5. This effect is notably strong at the end of the year, where the amount of VRES surplus in UK-N is large while hydropower production drops. Accordingly, the direction of power flowing on the UK-N cable gets shifted from UK-N towards NO5 at this point in time.

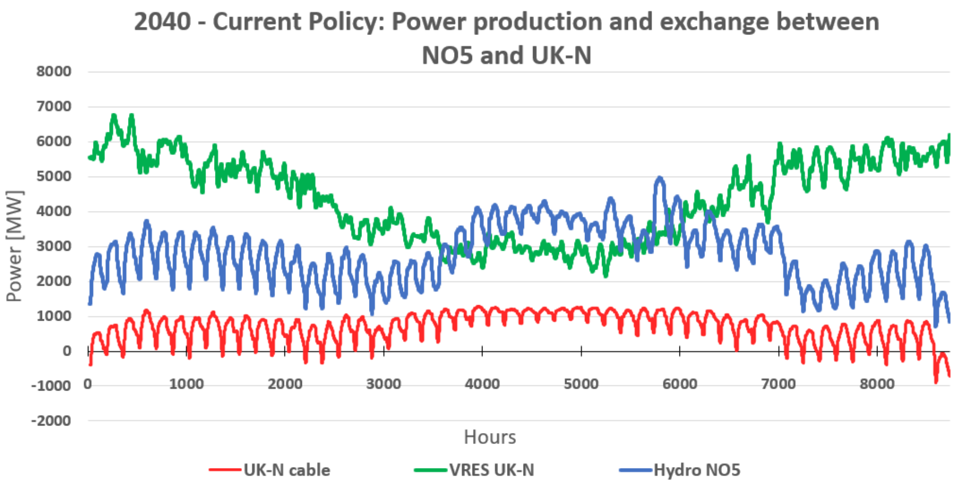


Figure 7.5: 2040 - Current Policy: Correlation between VRES production in UK-N, hydro production in NO5 and power flow in the UK-N cable. The graphs are illustrated by means of 24 hours MA.

Power consumed in Poland traced back to Norway, Sweden and Denmark

As seen in Figure 7.1, the polish power production increase following the implementation of the UK-N cable. One of the most prominent reasons for this is due to the changes in power contribution from Nordic countries to Poland. Table 7.4 shows how power consumed in Poland traced back to the Nordic countries changes when implementing the UK-N cable. It can be seen that the Nordic contribution of power to Poland drops with nearly 400GWh following the UK-N cable. This accounts for around 4/5 of the increased domestic production in Poland, which in Figure 7.1 was found to be of around 500GWh.

Table 7.4: Power consumed in Poland traced back to Norway, Sweden and Denmark.

	Without UK-N cable	With UK-N cable	Change
Norway	0,678 ‰	0,347 ‰	-0,31 ‰
Sweden	28,58‰	26,90 ‰	-1,68 ‰
Denmark	1,12 ‰	1,06 ‰	-0,06 ‰
Total [GWh]	5648	5264	-384

7.3.2 2040 - Wind&Solar

Figure 7.6 shows the power exchange between Norway and other countries with and without the UK-N cable. The changes in imports and exports in UK-N due to the UK-N cable are also highlighted. Appendix 9.3.1 gives the values used for plotting the diagrams.

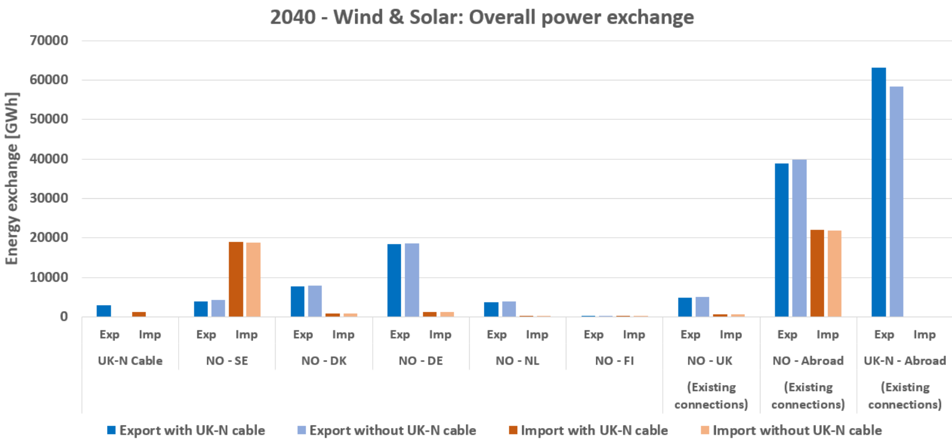


Figure 7.6: 2040 - Wind&Solar: Overview of exports and imports between Norway and neighbouring countries as well as power exchange between UK-N and its neighbouring nodes. See Appendix 9.3.1 for exact values

Similar to the results found in the previous section, Figure 7.6 shows that the UK-N cable indeed is mainly used for export purposes from Norway to UK-N. However, the difference in export and import is not as large as the one found in 2040 - Current Policy.

Likewise, Norwegian exports on other interconnections drop following the implementation of the UK-N cable, while the imports increase. The relative change is nevertheless smaller than what was found in 2040 - CP. The greatest change in power exchange is found towards Sweden where the export drops with 24%.

Again, the power exchange on the other interconnection between Norway and the UK decreases due to the UK-N cable. Besides, Table 7.3 indicated that UK-N has a large power surplus throughout the year, which is reflected in zero import to UK-N. The export from UK-N on other interconnections rise with 11% following the implementation of the UK-N cable.

Correlation power exchange through the UK-N cable and power production UK-N and NO5

Figure 7.7 shows the correlation between power flowing through the UK-N cable, VRES production in UK-N and hydro production in NO5. The figure supports Table 7.5 and Figure 7.9 indicating that the net export from Norway to UK-N in 2040 - CP is shifted towards a more balanced power exchange in 2040 - Wind&Solar. The VRES production of UK-N is at all times greater than the hydro generation in NO5. It is indeed highly volatile. The light-blue graph shows the same as seen for 2040 - CP, namely that hydro production is relatively great during summer. This creates the large net surplus for NO5, as seen in Table 7.3. The high production in UK-N makes UK-N having a net power surplus the whole year round.

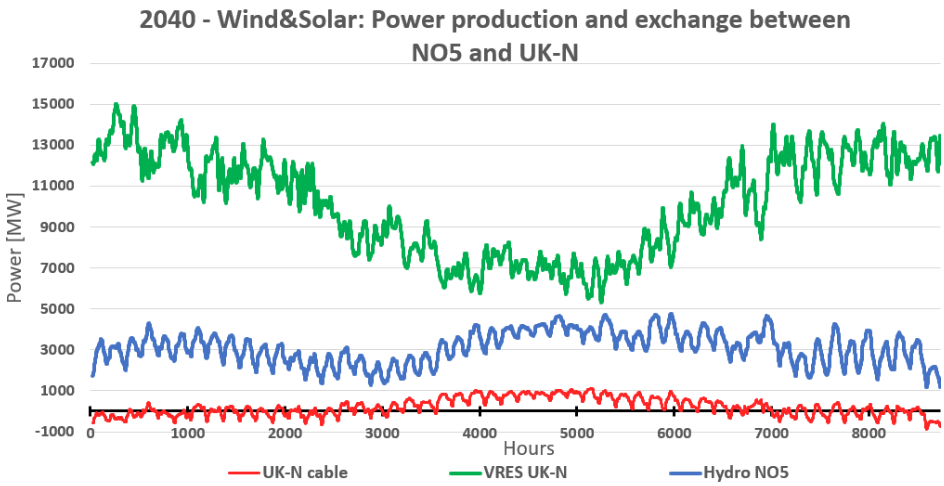


Figure 7.7: 2040 - Wind&Solar: Power exchange between UK-N and NO5 alongside VRES production in UK-N and hydro production in NO5. The graph is plotted with 24 hours MA for illustrative purposes.

7.3.3 Duration curves

In order to study the power exchange data and distribution of imports and exports various duration curves are created. Figure 7.8 shows the distribution of power traded on existing interconnections following the implementation of the UK-N cable. Keep in mind that the contribution of power trade from the UK-N cable to overall power exchange is omitted in order to create common foundation for comparison between the two graphs. As one can see from the graphs, the share of export from Norway on other cables is dropping following the implementation of the UK-N cable. The distributional effect following the implementation of the UK-N cable is biggest in the 2040 - CP scenario as the shift in the two curves is greater than in 2040 - Wind&Solar.

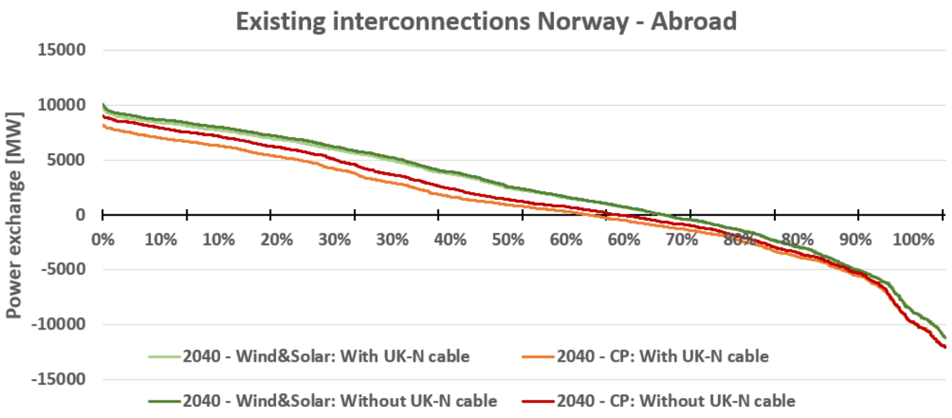


Figure 7.8: Duration curves of power exchange from Norway to neighbouring countries on already existing interconnections.

The duration curve for the power exchange on the UK-N cable is shown in Figure 7.9. The usage of the cable varies notably between the two scenarios. In 2040 - CP the cable is mostly used for export from NO5 to UK-N, while the power exchange is more balanced in both directions in 2040 - Wind&Solar.

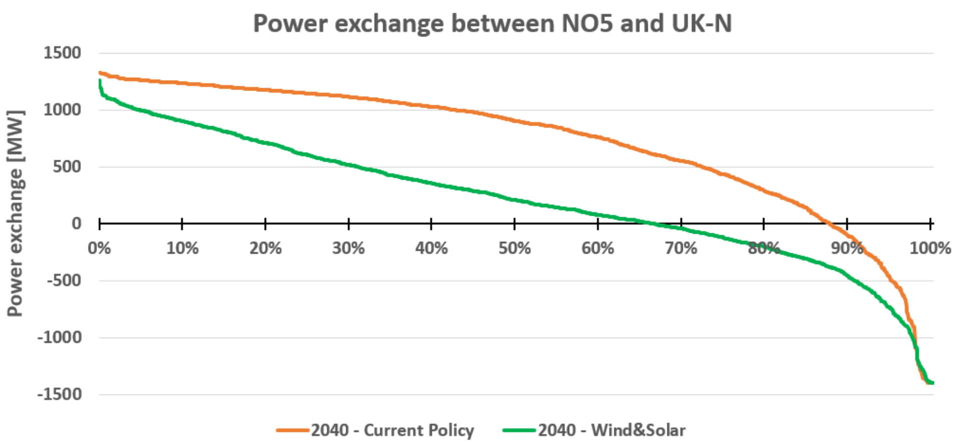


Figure 7.9: Duration curves showing the usage of the UK-N cable for both scenarios. Positive values define power flowing from N05 to UK-N.

Furthermore, Figure 7.10 shows the distribution curves for the power exchange between Norway and Germany. Similarly to what was seen in Figure 7.8 one can also here see that the distributional effect following the UK-N cable is strongest in 2040 - CP.

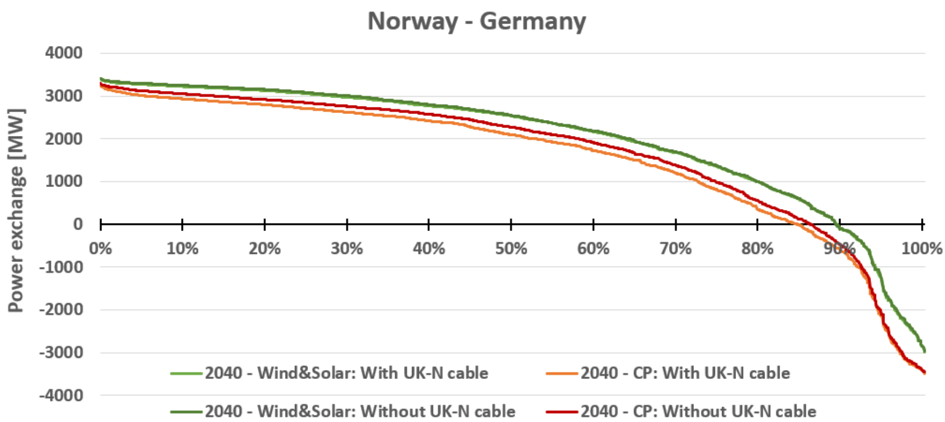


Figure 7.10: Duration curves of power exchange from Norway to Germany.

7.3.4 Comparison scenarios

There are multiple approaches for comparison regarding the changes in power exchange due to the UK-N cable. This section highlights some of the most important findings.

As seen from the previous sections, the export from Norway on other interconnections is reduced following the implementation of the UK-N cable. The opposite accounts for the import. However, the amount of power exchange on the UK-N cable is greater than the corresponding reduction on other interconnections. This yields an overall increased power exchange. Figure 7.11 sums up these differences. Further, it can be seen that the power trade in 2040 - Wind&Solar changes a lot compared to that of 2040 - Current Policy. See Appendix 9.3.1 for more detailed data.

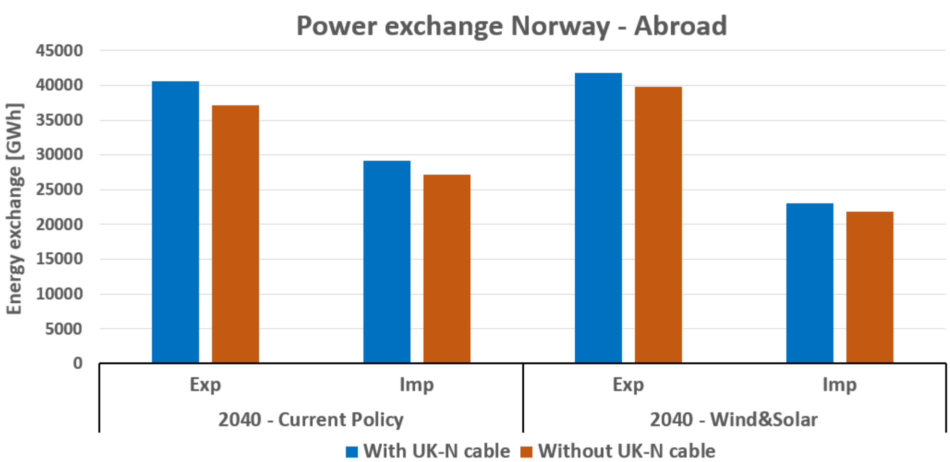


Figure 7.11: Bar chart showing power exchange between Norway and interconnecting countries with and without the UK-N cable.

Figure 7.11 shows that the overall Norwegian power trade increases the most in the 2040 - Current Policy scenario. That is to say, the overall power exchange increases most in both absolute and relative terms. Appendix 9.3.1 shows that the export rise by 9% while import with 7,5%. Furthermore, one can see that the export from Norway is greatest in 2040 - Wind&Solar. On the other hand, the import to Norway is greatest in 2040 - CP.

For further investigation regarding power prices and CO_2 emissions, the power exchange due to the UK-N cable is presented. Figure 7.12 shows the energy traded on the cable for both scenarios. Summer is defined as 1st of May to 31st of October.

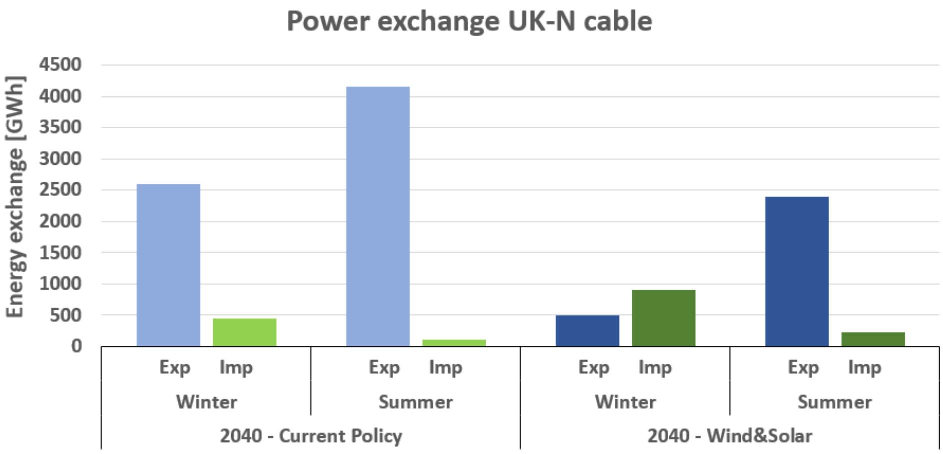


Figure 7.12: Export and import during summer and winter on the UK-N cable for both scenarios. Export is defined as power flowing from NO5 to UK-N.

Table 7.5: Distribution of export and import in terms of energy amounts and time usage.

	2040 - Current Policy			
	GWh	% Total	Hours	% Hours
Export	6 741	92,3	7 650	87,6
Import	559	7,7	1 086	12,4
	2040 - Wind&Solar			
	GWh	% Total	Hours	% Hours
Export	2 902	72,1	5 820	66,7
Import	1 126	27,9	2 916	33,3

Table 7.5 shows that for both scenarios the percentage of power flowing from NO5 to UK-N is greater than the percentage of hours used for exports from NO5 to UK-N. This indicates that the size of exported power is on average greater than the magnitude of import. The number of hours used for exporting purposes is reduced in the 2040 - WindSolar scenario, and conversely is the hours of import increased. This is also seen from

the duration curve of power exchange NO5 - UK-N (see Figure 7.9). The percentage of exported power from NO5 to UK-N is also in this scenario greater than the percentage hours of exports.

Power exchange Norway and Sweden

Figure 7.13 and 7.14 presents the power exchange seen between Norway and Sweden in both scenarios. The figures are created from 1-week moving averages. As one can see, Norway is importing power from Sweden throughout most of the year. For a smaller period during summer, however, do Norway export surplus hydropower to Sweden. Additionally, the introduction of the UK-N cable creates a greater shift in the power exchange curve in 2040 - CP than in 2040 - Wind&Solar.

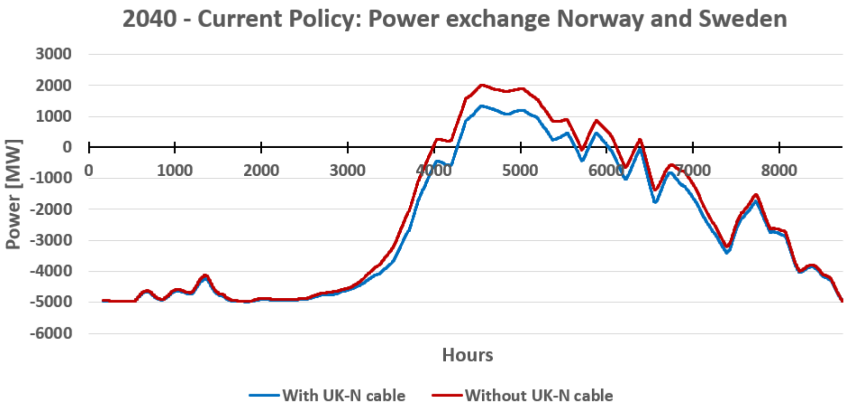


Figure 7.13: 2040 - Current Policy: Power exchange between Norway and Sweden presented through a 1-week moving average. Positive values indicate power flowing from Norway to Sweden.

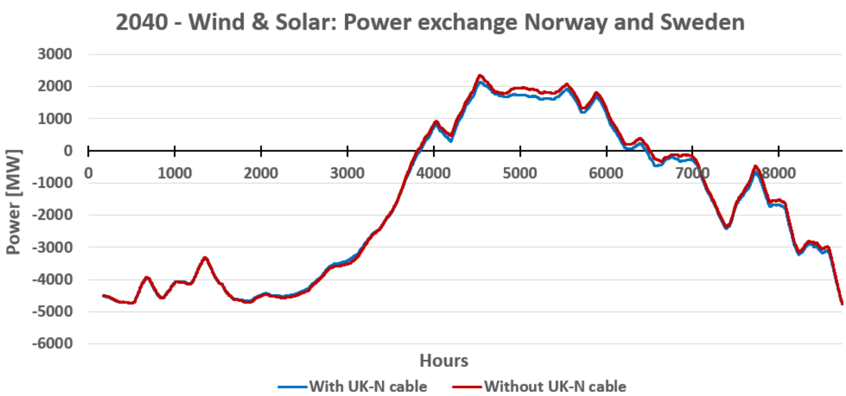


Figure 7.14: 2040 - Wind&Solar: Power exchange between Norway and Sweden presented through a 1-week moving average. Positive values indicate power flowing from Norway to Sweden.

Table 7.6 shows power flow tracing results regarding how much of the consumed Swedish power can be traced back to Swedish production. Both scenarios show that the Swedish dependency on domestic power production increases following the UK-N cable. The effect is the strongest in 2040 - CP.

Table 7.6: Percent of consumed Swedish power being traced back to Swedish production. Values are rounded to one decimal.

	2040 - CP		2040 - Wind&Solar	
	With cable	Without cable	With cable	Without cable
Summer	97,3%	96,2%	96,1%	95,8%
Winter	92,2%	92,2%	95,1%	95,1%

Power exchange on interconnection UK-S - France

Table 7.7 shows the maximum hourly power transferred on the interconnection UK-S - France for the simulations with and without the UK-N cable. It can be seen from the table that the maximum power exchanged in all four simulations do not exceed the original capacity of 12 600 MW. This will be further discussed in Section 8.2.

Table 7.7: Maximum hourly power transferred on the interconnection between UK-S and France in all four simulations.

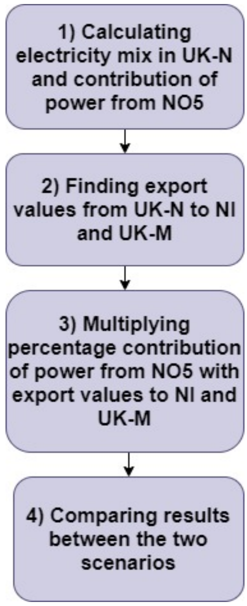
	2040 - CP		2040 - Wind&Solar	
Simulation	With UK-N cable	Without UK-N cable	With UK-N cable	Without UK-N cable
Transfer	11 303	12 052	7 264	7 601
Capacity	12 600	14 000	12 600	14 000

7.3.5 Simplified power flow tracing

Figures 7.15a and 7.15b show quasi-PFT, similar to the one described in Section 4.2, for the path Norway - UK-N cable - UK-N - NI & UK-M.

2040 - Current Policy			
1) El mix UK-N	Domestic production	Net export from NO5	Total
Value [GWh]	53 723	6182	59 905
Percentage [%]	90	10	100
2) Exchange	To NI	To UK-M	Total
From UK-N [GWh]	534	19 497	20 031
3) Path	NO5- NI	NO5 - UK-M	Total
Energy [GWh]	55	2 012	2 067
2040 - Wind&Solar			
1) El mix UK-N	Domestic production	Net export from NO5	Total
Value [GWh]	101 467	3 556	105 023
Percentage [%]	96,6	3,4	100
2) Exchange	To NI	To UK-M	Total
From UK-N [GWh]	3 553	55 209	58 762
3) Path	NO5 - NI	NO5 - UK-M	Total
Energy [GWh]	12	1 869	1 881
Comparison from 2040 - CP to 2040 - Wind&Solar			
4) Comparison	NO5 - NI	NO5 - UK-M	Total
Change [%]	-78	-7	-9

(a) Quasi-PFT starting from Norway (NO5) ending in NI and UK-M. import from Northern Ireland (NI) and UK-M are neglected.



(b) Flow chart showing workflow when conducting the quasi-PFT calculations.

Figure 7.15

The reader is encouraged to keep an eye on Figure 7.15a when reading this section. Firstly, the electricity mix in UK-N is established. At this point, the assumption that the electricity mix exported from UK-N is an even mix of domestic production and power exchange comes into play. As for the 2040 - CP scenario the percentage of power, stemming from the UK-N cable import to UK-N, makes up about 10% of total power, while the amount is down to 3,4% in the other scenario. This follows as a consequence of the increased domestic power production in UK-N and reduced power import on the UK-N cable, as shown in Table 7.3 and Figure 7.9. Other imports to UK-N, except the one coming from Norway, are neglected as they contribute to less 5 % of total import. Secondly, the distribution of exported power from UK-N towards UK-M and NI is found. Lastly, assuming that the exported power reflects the domestic electricity mix enables the possibility of finding Norwegian contribution to Northern Ireland and UK-M. Seen from Figure 7.15a the percentage of power stemming from Norway in the electricity mix of UK-N is dropping with 7% from scenario 2040 - CP to 2040 - Wind&Solar.

Results from power flow tracing

Table 7.8 compares the above results with what was found from the power flow tracing algorithm. The deviation in results will be further discussed in Section 8.2.

Table 7.8: Comparison of results between PFT and quasi-PFT.

	2040 - Current Policy	
Path	Norway - Northern Ireland	Norway - UK-M
Power flow tracing	70 GWh	1 755 GWh
Difference quasi-PFT	27%	-13%
	2040 - Wind&Solar	
Path	Norway - Northern Ireland	Norway - UK-M
Power flow tracing	78 GWh	1 288 GWh
Difference quasi-PFT	550%	-31%

7.4 CO_2 emissions

7.4.1 2040 - Current Policy

Figure 7.16 shows the change in CO_2 emissions in countries interconnected to Norway as well as the overall change for the whole simulated system.

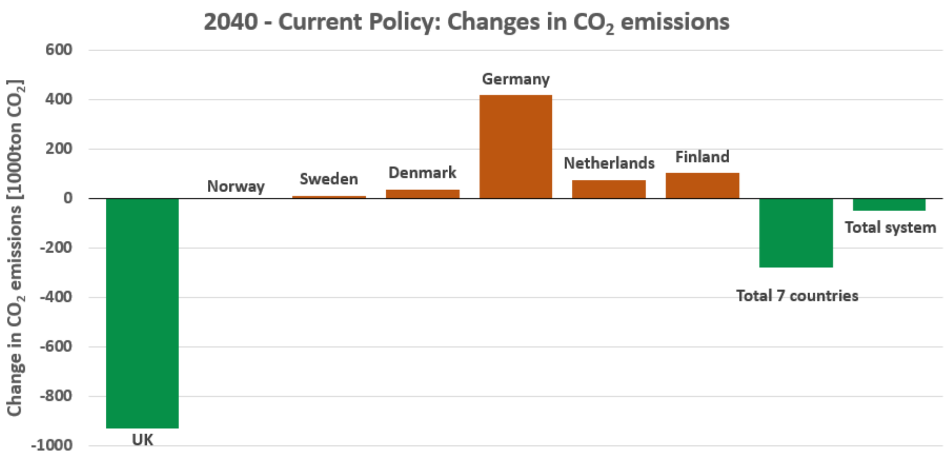


Figure 7.16: 2040 - Current Policy: Changes in CO_2 emissions for Norway and its interconnecting countries in addition to overall change in CO_2 emissions for the whole simulated system.

To give a more nuanced picture of the respective changes in CO_2 emissions Figure 7.17 divides the year into two seasons; summer and winter. Summer is again defined as 1st of May to 31st of October. Appendix 9.3.1 gives more detailed data.

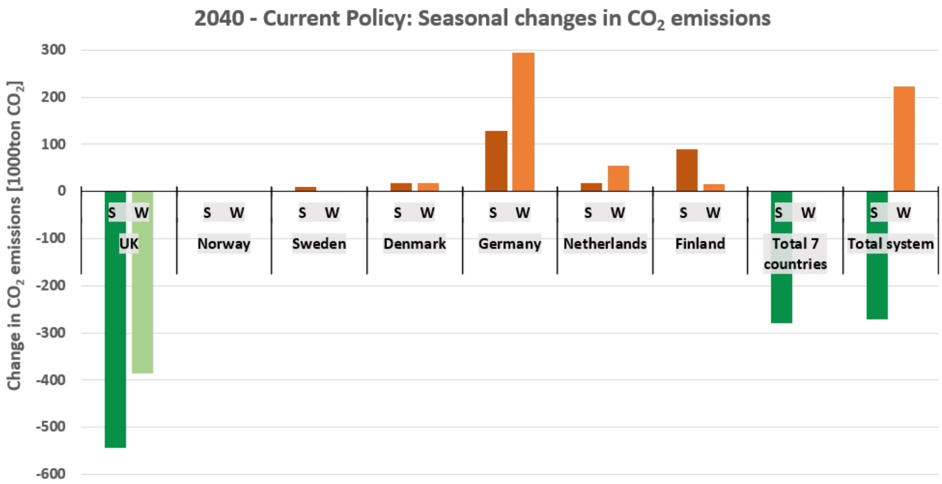


Figure 7.17: 2040 - Current Policy: Seasonal changes in CO_2 emissions for nodes studied.

Table 7.9 shows the total CO_2 emissions in the UK and the whole simulated system without the UK-N cable. The percentage reduction from the corresponding simulation without the UK-N cable is also presented.

Table 7.9: 2040 - CP: Total CO_2 emissions in the UK and the whole simulated system with the UK-N cable. Relative reduction from the simulation without the cable is also presented.

Node	UK	Total system
Total CO_2 emission	22,7Mton	600Mton
Reduction with UK-N cable	-4,1%	-0,008%

Figure 7.16 shows that UK is experiencing a reduction in CO_2 emissions of almost 1 Mton following the implementation of the UK-N cable. This corresponds to a reduction of around 4,1% from the emission level before implementing the UK-N cable. The reduction is greatest during summer, as seen from Figure 7.17. The savings are, however, to large degree offset by corresponding increased emissions in other nodes. This offsetting effect is strongest in Germany, which increases its emissions by more than 400 thousand tonnes. Around 3/4 of the extra German emissions come during winter. By just looking at the countries directly interconnected to Norway the CO_2 savings are down from 1 Mton to approximately 300 thousand tonnes. These savings comes solely during summer season. The increase in CO_2 emissions in other nodes, apart from the UK, is due to the distributional effects the UK-N cable has on other interconnections from Norway, as discussed in Section 3.1.2. The overall CO_2 emissions for the whole system drops during summer while rises during winter. Overall do this yield a net reduction of barely 50 thousand tonnes.

7.4.2 2040 - Wind&Solar

Figures 7.18 and 7.19 shows the CO_2 emissions for Norway and its interconnecting countries as well as the overall emissions for the whole system presented in Section 5.2. Appendix 9.3.1 gives more detailed data.

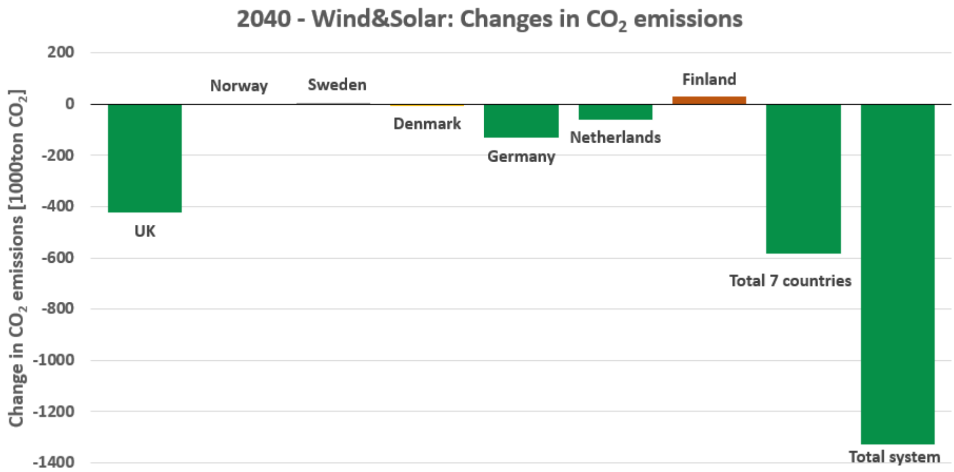


Figure 7.18: 2040 - Wind&Solar: Changes in CO_2 emissions for Norway and its interconnecting countries in addition to overall change in CO_2 emissions for the whole simulated system.

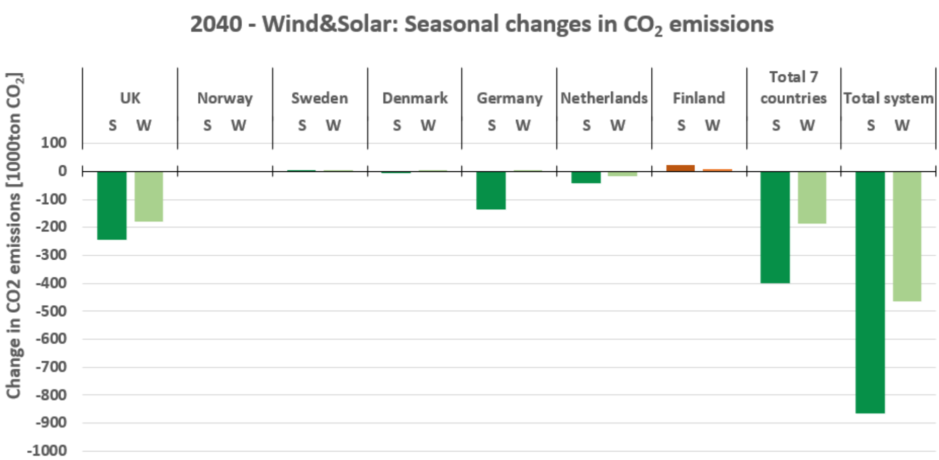


Figure 7.19: 2040 - Wind&Solar: Seasonal changes in CO_2 emissions for nodes studied.

Table 7.10 shows the total CO_2 emissions in the UK and the whole simulated system with the UK-N cable. The percentage reduction from the corresponding simulation without the UK-N cable is also presented.

Table 7.10: 2040 - Wind&Solar: Total CO_2 emissions in the UK and the whole simulated system with the UK-N cable. Relative reduction from the simulation without the cable is also presented.

Node	UK	Total system
Total CO_2 emission	8,6Mton	559,9Mton
Reduction with UK-N cable	-4,7%	-0,2%

Figure 7.18 shows that the UK reduces its CO_2 emissions with approximately 0,4 Mton. Table 7.10 shows that this equals a reduction of 4,7% compared to emission level without the UK-N cable. Further, the majority of CO_2 reductions tend to happen during summer. The overall CO_2 emissions reduce with more than 1,3 Mton. Interestingly, as presented in Section "Power production and consumption" 7.2, the distributional effects regarding carbon emissions unfolds in quite a different way compared to in 2040 - CP. Alongside UK, both Denmark, Germany and the Netherlands also reduce their CO_2 emissions.

7.5 Power flow tracing

7.5.1 2040 - Current Policy

Figure 7.20 shows the change in CO_2 emissions following the implementation of the UK-N cable from a consuming point-of-view. Appendix 9.3.1 gives a more detailed dataset.

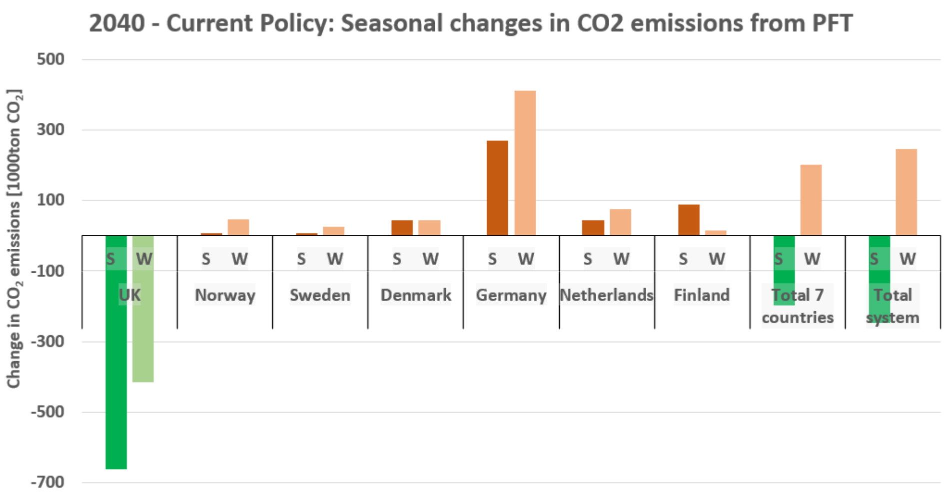


Figure 7.20: 2040 - Current Policy: Seasonal changes in CO_2 emissions allocated from a consuming point-of-view.

Figure 7.21 shows the development of CO_2 intensity in consumed electricity mix for UK, UK-N and Norway. A drop in CO_2 intensity is seen in UK following the implementation of the UK-N cable. Oppositely, a small upward shift is seen in Norway, especially during winter.

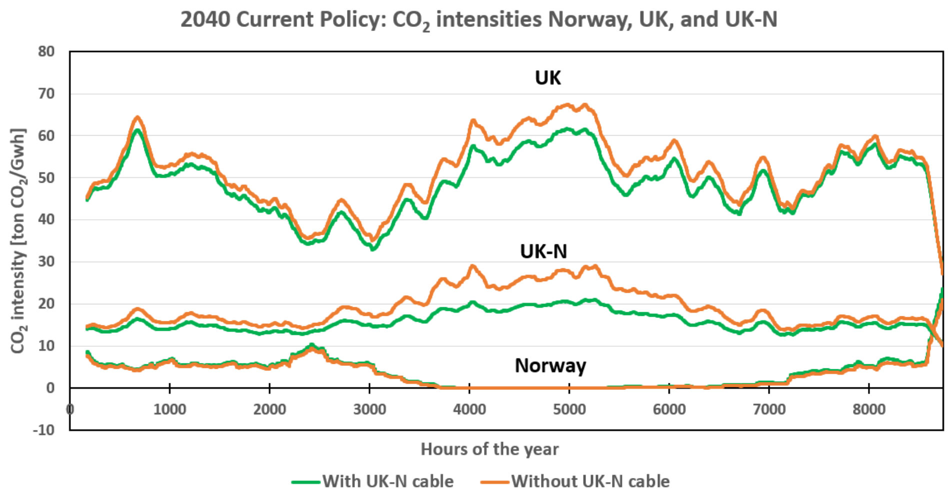


Figure 7.21: 2040 - Current Policy: CO_2 intensity of consumed electricity with and without UK-N cable for the areas UK, UK-N and Norway.

7.5.2 2040 - Wind&Solar

Figure 7.22 shows changes in CO_2 emissions calculated from power flow tracing. Appendix 9.3.1 gives a more detailed dataset.

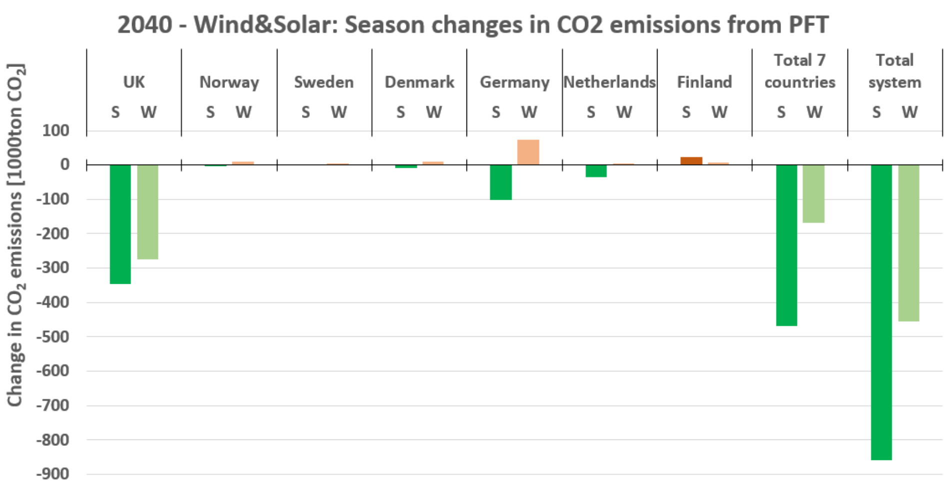


Figure 7.22: 2040 - Wind&Solar: Seasonal changes in CO_2 emissions allocated from a consuming point-of-view.

Figure 7.23 shows the development of CO_2 intensity in consumed electricity mix for UK, UK-N and Norway. As seen from the figure, the intensity in Norway and UK-N is now in more or less the same order of magnitude. The reduced CO_2 intensity found in 2040 - CP is not as clear in this scenario.

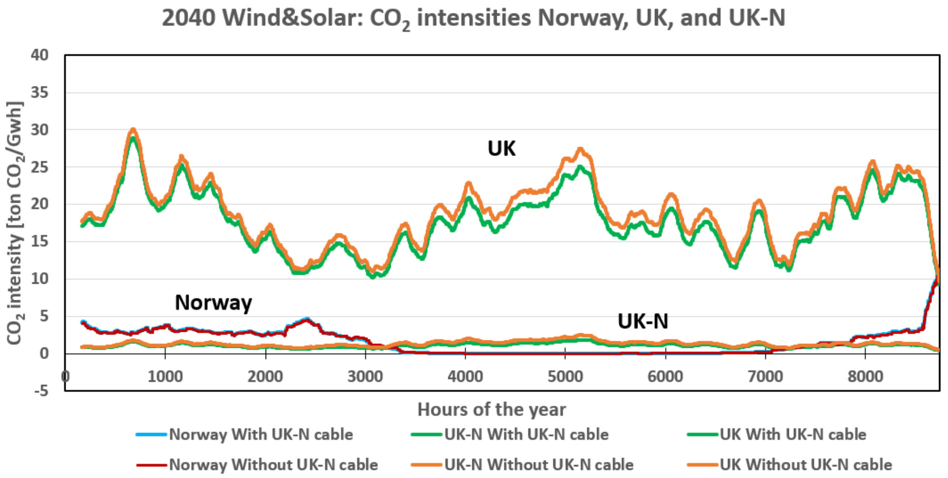


Figure 7.23: 2040 - Wind&Solar: CO_2 intensity of consumed electricity with and without UK-N cable for the areas UK, UK-N and Norway.

7.5.3 Comparison CO_2 emission allocation from producing and consuming point-of-view

Figure 7.24 and 7.25 compares CO_2 emission allocation from domestic production and domestic consumption. The EMPS label reflects the domestic produced CO_2 emissions calculated by the EMPS model, whilst the PFT label reflects CO_2 emissions related to domestic consumption.

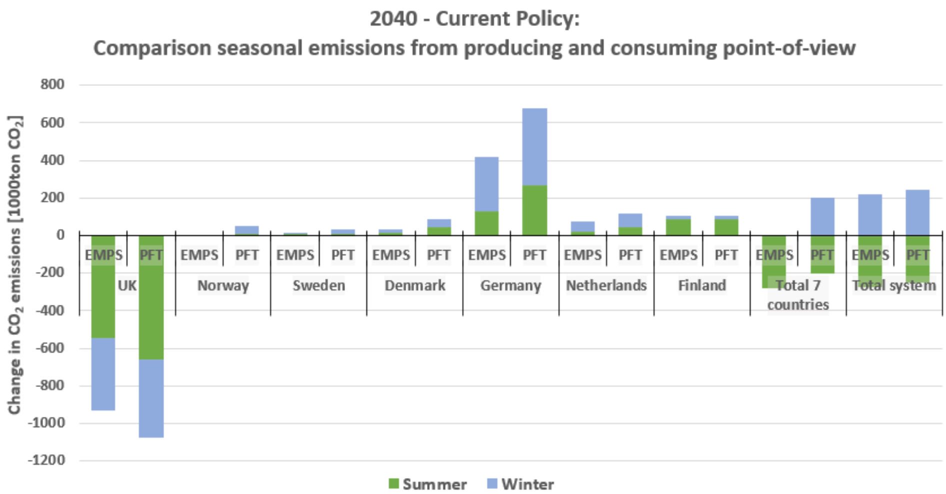


Figure 7.24: 2040 - Current Policy: CO_2 allocation from a producing and consuming point-of-view.

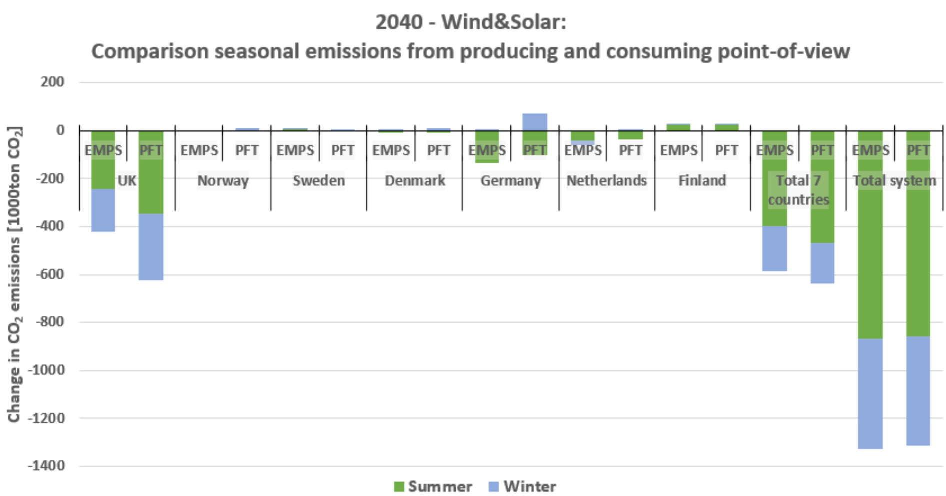


Figure 7.25: 2040 - Wind&Solar: CO_2 allocation from a producing and consuming point-of-view.

There are several interesting elements seen from Figures 7.24 and 7.25. Firstly, for the countries interconnected to Norway, except UK, it seems that the CO_2 emissions related to domestic consumption are greater than domestic produced CO_2 emissions. This implies that the distributional effects of the UK-N cable observed in Section 7.4 are even stronger when considering consumption as the main driving force for CO_2 emissions. In the case of the UK, however, the results are quite the opposite. From both graphs it can be seen that the actual savings of CO_2 emissions related to British consumption is greater than first calculated from the EMPS model. The power flow tracing calculates that, in 2040 - CP, the net CO_2 emission savings due to consumption in UK is of almost 1,1 Mton. That is around 200 thousand tons CO_2 saved compared to emissions from domestic production. Summing up for the neighbouring nodes of Norway in 2040 - CP, it can be seen that the net saving found in Section 7.4 of 0,3 Mtons has dropped to more or less zero.

In the 2040 - Wind&Solar scenario the power flow tracing finds the CO_2 emissions in UK to reduce from 0,4 to 0,6 Mtons. The distributional effects of the cable is indeed rather unclear. Moreover, the observant reader might notice the inconsistency between the change in total CO_2 emissions for the whole system between EMPS and PFT. Naturally, these emissions should be of the same order of magnitude as the simulation is done on a closed system. This topic will be further presented in the following section and discussed in Section 8.3.

7.5.4 Deviation total CO_2 emissions from producing and consuming point-of-view

When performing power flow tracing, the total amount of CO_2 emissions allocated from consumption turns out to deviate somewhat from the total CO_2 emissions calculated by the EMPS model. Figure 7.26 shows these deviations. In the 2040 - CP scenario, the PFT is operating with around 1‰ increased overall CO_2 emissions, while the difference in 2040 - Wind&Solar is of approximately 0,2‰.

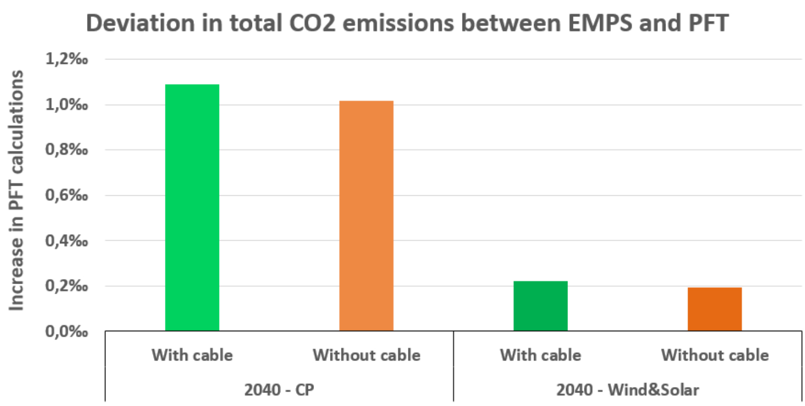


Figure 7.26: Deviation in overall CO_2 emissions when allocating from a consumption instead of production. Keep in mind that the y-axis represents per mille [‰] increase of total CO_2 emissions found from PFT compared to that of EMPS.

7.6 Power prices

As presented in Section 2.2.4, there are many economic aspects following the implementation of interconnecting resources and VRES. This section will emphasise power prices with respect to power flows and RES production. Bear in mind that many of the following graphs are illustrated by means of 168 hours moving averages (MA), in other words; 1-week moving averages.

7.6.1 2040 - Current Policy

The immediate effect the UK-N cable has on the power prices varies greatly between UK-N and NO5. As seen in Figure 7.27, the power prices in NO5 increase following the implementation of the UK-N cable. The effect is the strongest during summer. The increased power prices in NO5 is also found during winter, though to a much smaller degree. On the other hand, the change in power price in UK-N due to the UK-N cable seems negligible. The power prices in UK-N and NO5 do overall tend to be in the same order of magnitude during winter.

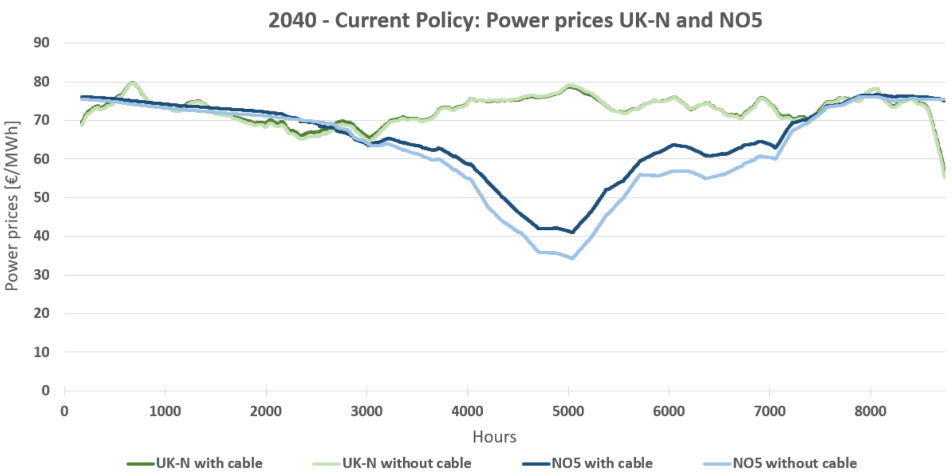


Figure 7.27: Power prices in UK-N and NO5 with and without the UK-N cable. Keep in mind that it is used 168h moving averages (1-week MA) for illustrative purposes.

To further study how power prices are affected by the UK-N cable, Figure 7.28 presents the price difference between UK-N and NO5. The price difference is found by subtracting the Norwegian price from the price of UK-N. Besides the increased price difference during summer, it is easily seen that the UK-N cable most of the time lowers the price differences.

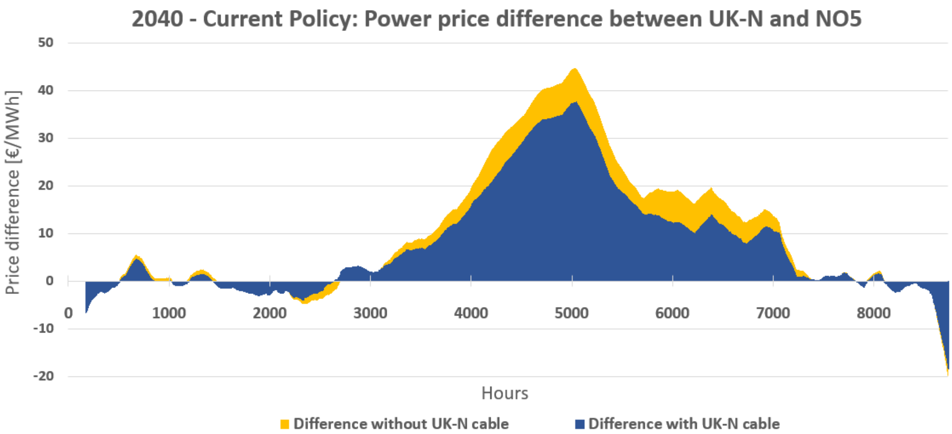


Figure 7.28: 2040 - Current Policy: Power price difference between UK-N and NO5. 168 hours MA (1-week MA) are used for illustrative purposes.

Table 7.11 shows how the average power prices during winter and summer changes with the implementation of the UK-N cable. The price differs the most in NO5 during summer, with an average increased price of 4,5€/MWh following the UK-N cable. This coincides with what was seen in Figure 7.27. Interestingly, the power price in UK-N is also seen to increase in both seasons. The power prices do overall on average increase with 2,5€/MWh and 0,3€/MWh for NO5 and UK-N, respectively.

Table 7.11: 2040 - CP: Average seasonal price variations with and without the UK-N cable for both NO5 and UK-N.

	NO5			UK-N		
Power prices [€/MWh]	Winter	Summer	Total	Winter	Summer	Total
Without UK-N cable	72,8	53,1	62,9	71,4	73,4	72,4
With UK-N cable	73,3	57,6	65,4	71,9	73,4	72,7
Change	0,5	4,5	2,5	0,5	0,1	0,3
Relative change	0,7%	8,4%	4%	0,7%	0,1%	0,4%
	Norway			UK		
Without UK-N cable	71,7	53,8	62,7	71,6	73,4	72,5
With UK-N cable	72,3	57,6	64,9	72,1	73,5	72,8
Change	0,6	3,8	2,2	0,5	0,1	0,3
Relative change	0,9%	7%	3,5%	0,7%	0,2%	0,4%

Figure 7.29 shows how the power exchange on the UK-N cable varies in correlation with the power price difference in bidding zone UK-N and NO5. The price difference is again found from taking the hourly price in UK-N and subtracting with the hourly price in NO5. The figure shows that, for most of the year, the Norwegian price level is lower than in UK-N. This accounts especially during summer, where Figure 7.5 indicated that NO5

experienced a hydropower surplus, while UK-N conversely underwent an overall deficit in VRES production. Consequently, the UK-N cable is used for exporting purposes to UK-N, due to bottleneck trading, as explained in Section 2.2.4. The periods where prices in UK-N is lower than in NO5 is mainly caused by great VRES production and deficit hydropower in NO5 during winter.

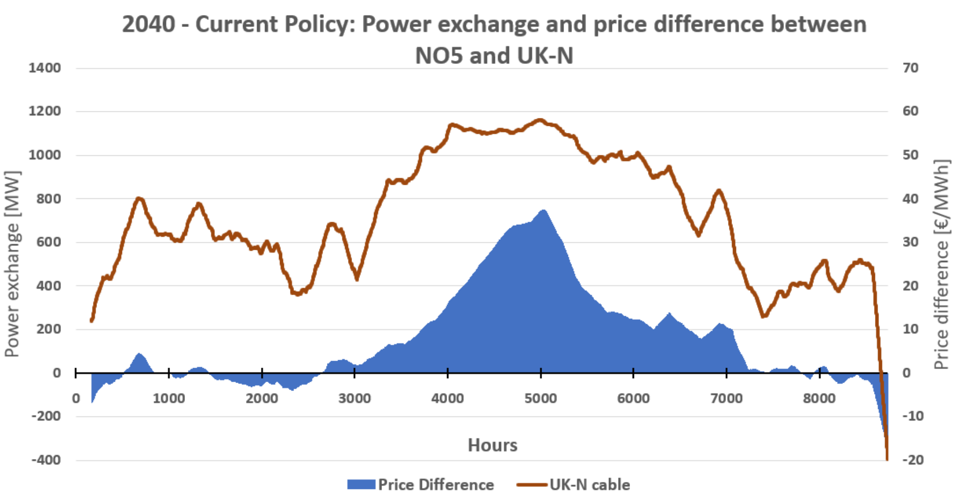


Figure 7.29: 2040 - Current Policy: How amount of power traded on the UK-N cable varies in line with the price difference on each end of the cable. Price difference is calculated as price in UK-N subtracted with price in NO5.

A drawback with the utilization of moving averages becomes evident in Figure 7.29. At first glance, it seems that the UK-N cable is solely used for export from Norway to UK. Table 7.5, however, indicates that this is not the case. Hence, it is important to be critical when studying the graphs based on moving averages.

Further, the correlation between power exchange through the UK-N cable and bottleneck trading is studied more in detail. A week with greater-than-average power import to NO5 from UK-N is chosen. Figure 7.30 shows power prices plotted against power exchange on the UK-N cable. The contribution of power from NO5 to the electricity mix in UK-M found from power flow tracing is also drawn. In order to draw all this information into a meaningful graph, the result from PFT is scaled 10x and plotted towards the right-hand axis. Due to the scaling factor, the actual percentage power in UK-M traced back to NO5 is therefore found by dividing the y-value with 10. The price in UK-M is more or less equal to the price in UK-N at all times and is therefore not visible on the graph.

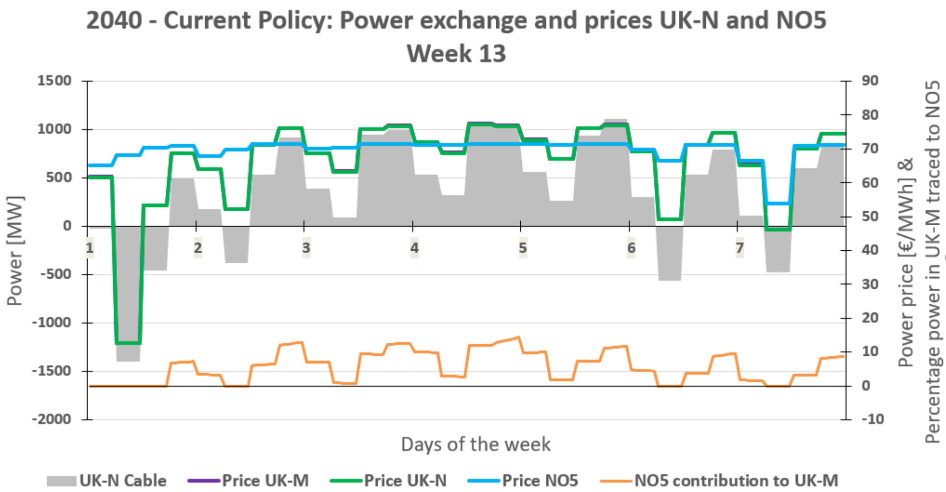


Figure 7.30: 2040 - Current Policy: Power exchange on the UK-N cable unfolds in week 13 in correlation with its end-point power prices. The percentage power in UK-M traced back to NO5 is also plotted with a scaling factor of 10 towards the right-hand axis.

From Figure 7.30 the correlation between the power price difference of NO5 and UK-N and the direction and size of power traded seems quite clear. Undoubtedly, at times where the power price is much lower in UK-N than in NO5, the cable is used to import power to NO5. The opposite trading direction is seen when Norwegian power prices are lower than prices in UK-N. However, there are periods where power is exported from NO5 to UK-N even though prices are equal or the price level in UK-N is somewhat smaller than in NO5. Section 8.4 will investigate this further.

The power flow tracing shows that some power stemming from NO5 ends up in UK-M. This confirms the idea of UK-N functioning partially as a transit node for power from NO5. The transiting effect increase with increased power exchange on the UK-N cable. Furthermore, it can be seen that the power prices in UK-N is highly fluctuating. The power prices do, for week 13, turn out to vary from around 15€/MWh up to a roof of about 75€/MWh. The price does, nonetheless, fluctuate most of the time around the more stable Norwegian power price. This corresponds well with what was seen in Figure 7.27, where the prices were relatively equal until week 19 (around 3200 hours).

Finally, power production and exchange between UK-N and NO5 is studied. Figure 7.31 shows the power exchange on the UK-N cable as well as the VRES production in UK-N and hydro production in Norway. The immediate correlation between VRES production and power exchange at the UK-N cable is somewhat unclear. As seen, the magnitude of traded power is greatest during daytime.

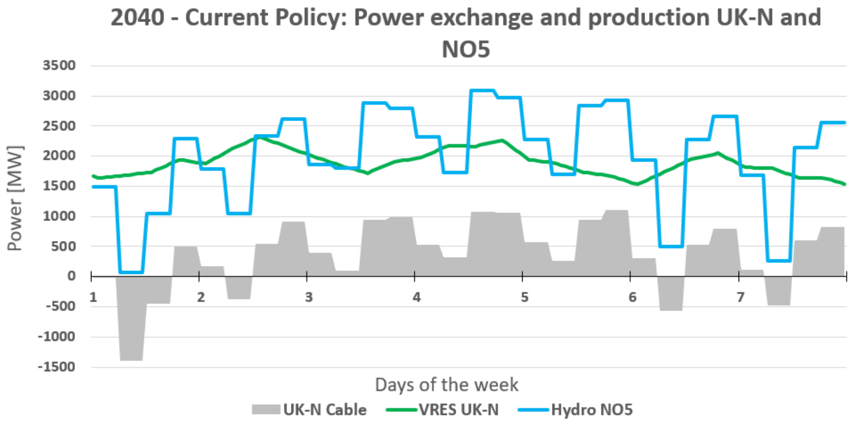


Figure 7.31: 2040 - Current Policy: VRES production in UK-N, hydro production in NO5 alongside the power exchange on the UK-N cable for week 13 in 2040 - CP

7.6.2 2040 - Wind&Solar

Figure 7.32 shows how the power prices in UK-N and NO5 develop with the implementation of the UK-N cable for scenario 2040 - Wind&Solar. The price level in UK-N is seen to increase overall following the UK-N cable, while the same accounts for NO5 during summer. The price level of UK-N is significantly lower than what was found in 2040 - CP. The large power surplus in UK-N shown in Figure 7.7 is one of the driving forces behind this shift in price level. In NO5, on the other hand, the price level can be considered to be in somewhat the same range as before.

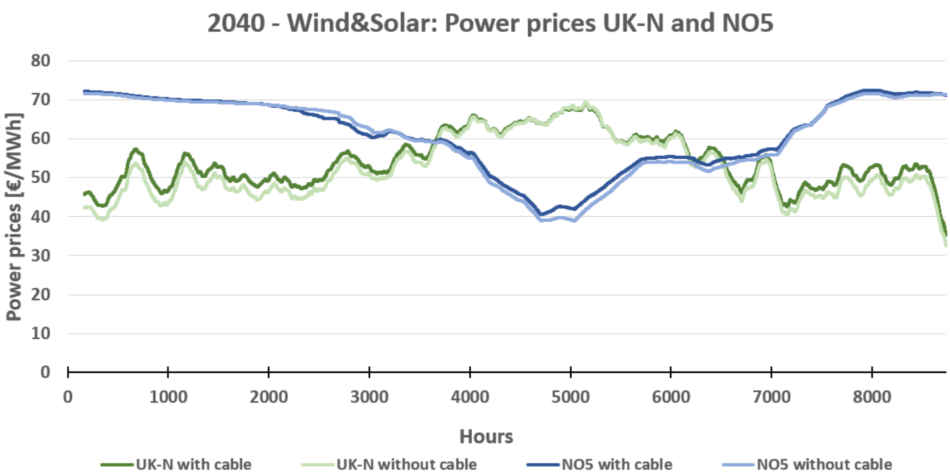


Figure 7.32: 2040 - Wind&Solar: Power prices in UK-N and NO5 with and without the UK-N cable. Keep in mind that it is used 168h moving averages (1-week MA) for illustrative purposes.

Table 7.12 shows the seasonal development in power prices following the UK-N cable. The power price in NO5 increases the most during summer, while there is no change during winter. As for UK-N, the price differs the most during winter with 2,9€/MWh. Overall do the price level increase with 0,6€/MWh and 1,9€/MWh for NO5 and UK-N, respectively.

Table 7.12: Seasonal price variations with and without the UK-N cable for both NO5 and UK-N.

Power prices [€/MWh]	NO5 Winter	NO5 Summer	NO5 Total	UK-N Winter	UK-N Summer	UK-N Total
Without UK-N cable	69,4	52,4	60,8	46,9	57,6	52,3
With UK-N cable	69,4	53,6	61,5	49,8	58,5	54,2
Change	0	1,2	0,6	2,9	0,9	1,9
Relative change	0%	2,4%	1,1%	6,3%	1,6%	3,7%
	Norway			UK		
Without UK-N cable	68,0	52,3	60,1	58,2	62,3	60,3
With UK-N cable	68,2	53,3	60,7	58,9	62,3	60,6
Change	0,2	1,1	0,6	0,7	0,0	0,3
Relative change	0,2%	2%	1%	1,2%	-0,1%	0,6%

Figure 7.33 shows that the implementation of the UK-N cable partly reduces the overall price difference between UK-N and NO5.

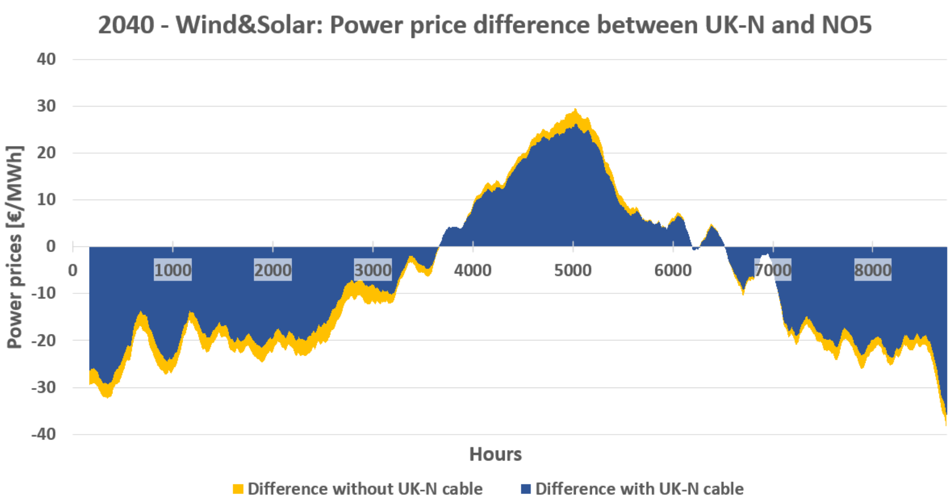


Figure 7.33: 2040 - Wind&Solar: Power price difference between UK-N and NO5. 168h MA (1-week MA) are used for illustrative purposes.

Figure 7.34 demonstrates more clearly the effect price difference between UK-N and NO5 has on the UK-N cable power flow. The lower price level in UK-N during winter makes a large share of the power to flow in the direction towards NO5. Similar to 2040 - CP, the UK-N cable is solely used for export of Norwegian hydropower during summer. This goes hand-in-hand with the low price level in NO5 compared to UK-N during summer.

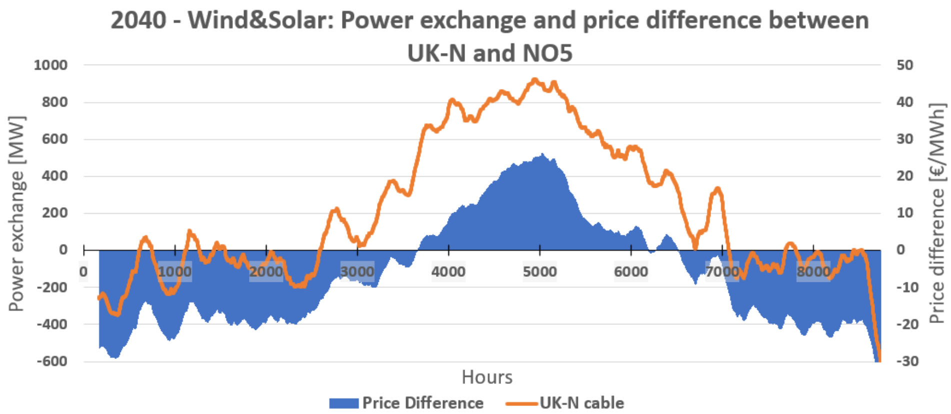


Figure 7.34: 2040 - Wind&Solar: Correlation power flow on the UK-N cable and difference in power price between UK-N and NO5. The graph is plotted by means of 168h (1-week) moving averages for illustrative purposes.

Finally, the correlation between power exchange, RES production and power prices intra-weekly is studied.

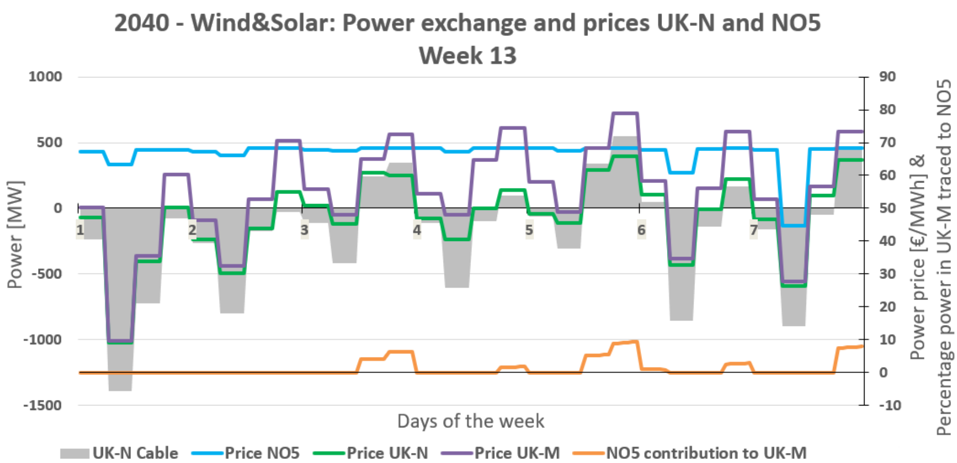


Figure 7.35: 2040 - Wind&Solar: Power exchange on the UK-N cable in week 13 in correlation with its end-point power prices. The percentage power in UK-M traced back to NO5 is also plotted with a scaling factor of 10 towards the right-hand axis.

Similar to scenario 2040 - CP, Figure 7.34 shows that there is a strong correlation between price difference and power exchange. In this case, the price for UK-M is also plotted. During most of the week, the power price is much lower in UK-N than in NO5, thus creating power export from UK-N to NO5. However, there are periods where the difference in the two prices becomes somewhat smaller and the direction of power flow in the cable reverts towards UK-N. This tends to coincide with periods where the UK-M price is greater than in NO5. The orange line indicates that the NO5 contribution of power to UK-M increases significantly when the price in UK-M is bigger than both NO5 and UK-N. The power price in UK-N continues to be highly fluctuating, ranging from 15 €/MWh to 65 €/MWh. Norwegian power price lays flat of around 70 €/MWh apart from one major drop down to 45 €/MWh.

Ultimately, the VRES production in UK-N, the hydro production in NO5 and the power exchange are plotted together in Figure 7.36. The graphs are plotted without a secondary y-axis in order to better illustrate the relationship between the large VRES production in UK-N and the power exchange on the UK-N cable.

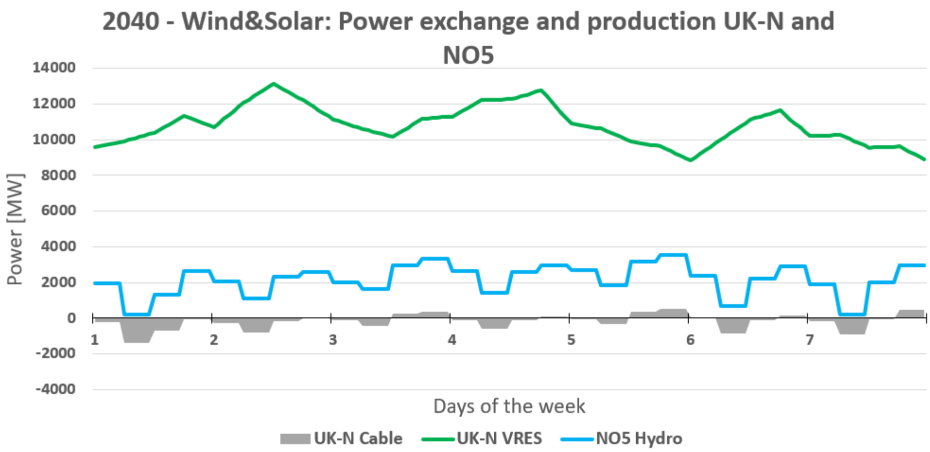


Figure 7.36: 2040 - Wind&Solar: VRES production in UK-N, hydro production in NO5 alongside the power exchange on the UK-N cable for week 13

Chapter 8

Discussion

This chapter will be divided into multiple sections, handling and discussing the topic presented in chapter Results. It is divided as follows:

Table 8.1: Structure of "Discussion" chapter

Section	Results
8.1	Power production and consumption
8.2	Power exchange between nodes
8.3	CO_2 emissions
8.4	Power prices
8.5	Uncertainties and limitations

8.1 Power production and consumption

Section 5.4.1 about the EMPS model presented how the power plant input data vary between different plant technologies. Some of the power plants are simulated with an upper energy production limit given as an exogenous variable. This accounts for VRES production, nuclear and bio plants and partially for hydropower. In particular, the fact that VRES production is given by means of hourly time series has an important consequence. That is to say, the pattern of VRES production remains the same for the simulation with and without the UK-N cable. Evidently, the balancing properties of the UK-N cable, as well as facilitation of higher exploitation of wind power and solar power become negligible. On the other hand, in the case of thermal plants having their capacity set as input parameters, the overall production can be considered as an endogenous variable. The capacity decides how much energy can maximum be produced at any instant when beneficial. A greater capacity could potentially increase the production, although only if it is economically beneficial. The aftermath of the static VRES production will be further discussed later in Section 8.5.

For the following discussions some of the most noteworthy from Section 7.2 is probably the seasonal power surplus/deficit in NO5 and UK-N. The power surplus has, naturally, a strong correlation with the power prices in the areas. In parallel, it is therefore also related to the power exchange seen on the UK-N cable. As seen from Table 7.3, the surplus in UK-N is more than four times greater in the 2040 - Wind&Solar scenario compared to 2040 - CP. The motivation behind this is to create an optimistic, but indeed realistic, picture of the potential benefits following the implementation of an interconnection cable in a system dominated by VRES production. The observant reader might have noticed that the Norwegian hydro production curve seen in Figure 9.3 do, to some degree, deviate from the historical graph presented in Chapter "Literature Review" by NVE (Figure 2.4). One of the most noticeable reasons to this is the fact that an extended share of the Norwegian demand is covered by wind power during winter for the simulated scenario. This contributes to shift the hydro production peak to mid-summer after having major water inflows during spring. Increased interconnection capacity also stimulates increased hydro production during summer. Furthermore, a detailed view of production is also given for Sweden as a whole. As Sweden is the biggest power trading partner of Norway, the distributional effects following the UK-N cable will be of special interest.

When it comes to the changes in the production mix data seen in Figures 7.1 and 7.2 it, can at first, sight seem like the UK-N cable brings major changes in the overall production patter for the rest of the system. However, Table 7.2 shows that this is not the case, as the greatest change is found to apply to gas-fired production with around 1% drop in both scenarios. There are mainly two reasons why power production from gas plants drops the most. Firstly, in the UK thermal production is mostly dominated by gas-fired plants. As the UK-N cable provides more Norwegian hydropower to UK, the demand for domestic thermal electricity production decreases. Secondly, gas-fired power production is relatively costly compared to that of nuclear and, to some degree, also to that of coal [13]. Hence, production from gas power plants reduces first in most European countries. That being said, a more interesting observation from the figures is which countries do increase their production and which do not. In 2040 - CP, a pattern is formed where countries connected to Norway through existing interconnections are increasing their production (e.g., Germany, the Netherlands and Sweden). On the other hand, countries connected to the UK tend to lower their production with the UK-N cable (Spain, France and Belgium). The same pattern is not found in 2040 - Wind&Solar, whereas most countries tend to decrease their production following the UK-N cable. Some of these effects will be further investigated in the upcoming section regarding power exchange.

From Table 7.2 it was seen that the total power production dropped slightly in both scenarios when implementing the UK-N cable. At first glance, this can seem quite unreasonable as consumption is held constant before and after implementing the UK-N cable. However, as explained in Chapter 5 "EMPS Model", this is due to the fact that there are some time steps in the simulations where an external sink is used to "consume" production that slightly exceeds simulated consumption. The topological alteration of the grid that the UK-N cable creates changes the utilization of these sinks, which again reduces the overall power production.

8.2 Power exchange

In this section the power exchange and distributional effects between Norway and its interconnecting neighbours will be discussed. Furthermore, transit effects and some changes in the power flow pattern on Continental Europe will be investigated.

As seen from the tables and figures in Section 7.3, the UK-N cable's implementation reduces export and increases imports on existing interconnections to Norway. The effect is especially evident in 2040 - CP. This coincides with what NVE presented in its report (see Section 3.1.2). These distributional effects are, however, not as clear in 2040 - Wind&Solar. The major power surplus in Norway, Sweden and the UK contribute to maintain a relatively stable power exchange between Norway and neighbouring countries despite the implementation of the UK-N cable. Due to the power surplus, the magnitude of power exports from Norway is greater than in 2040 - CP. Oppositely, power imports are smaller than 2040 - CP.

All in all, Figure 7.11 shows that power exchange between Norway and neighbouring countries increases following the UK-N cable in both scenarios. This means that the power exchange on the UK-N cable is greater than the reduced power exchange on existing interconnections. Interestingly, both simulated scenarios do indicate that the UK-N cable affects power exchange on existing cables to less degree than what was found in the NVE report.

With the aforementioned as a backdrop, an interesting discussion arises; How might the reviewed overall power trades affect Norwegian bottleneck income? Section 3.1.2 shows that NVE concludes with a reduction in traded volumes on existing interconnections, which would reduce the overall congestion income for Statnett. The EMPS simulations show that the reductions in traded volumes might not be as great as presented by NVE. Consequently, the losses in congestion income can be less than first presented in the NVE report. Admittedly, the scenario constructions and simulations done in this thesis do differ from that of NVE. Nevertheless, the EMPS results indicate that the overall Norwegian power exchange, laying the foundation for NVEs calculations of losses in bottleneck income, is a topic definitely up for discussion and revision.

When it comes to power exchange between Norway and Sweden, which is the greatest trading partner of Norway, there are some interesting findings. From Figure 7.13 and 7.14 one can see that the export from Norway to Sweden drops during summer in both scenarios. However, there is a clear difference in how much the export drops between the two scenarios. That is to say, the exports are dropping more in the 2040 - CP than in 2040 - Wind&Solar. One of the most important reasons to this is that the energy production in Sweden is to much higher degree dominated by VRES production in 2040 - Wind&Solar. Hence, to counteract the drop in VRES production typically seen during summer, Sweden must import more power - some coming from Norway. Consequently, the drop in power export from Norway to Sweden during summer is not as great in 2040 - Wind&Solar as in 2040 - CP where Swedish production is more reliant on nuclear power. The results from power flow tracing supports this idea. Table 7.6 shows that during summer in 2040 - CP Sweden is to larger degree covering domestic consumption by domestic (mostly nuclear) production when introducing the UK-N cable. In 2040 - Wind&Solar, however, the nuclear capacity is lower. Hence, power flow tracing shows that foreign contribution of power, which covers Swedish consumption remains relatively stable despite the implementation of the UK-N cable. Overall, this underlines the advantage of strong interconnections in power systems dominated by VRES.

8.2.1 Duration Curves

From Section 7.3.3 it can be seen multiple interesting results. First of all, for power exchange on existing interconnections, the shift in duration curve is greater in 2040 - CP than in 2040 - Wind&Solar. This corresponds with the discussed change in the distributional effects between the two scenarios. The downshift in duration curve in 2040 - CP indicates that the existing interconnectors are to larger degree used for importing purposes following the UK-N cable. The large power surplus seen in 2040 - Wind&Solar supports the idea of Norway as a net exporter of power, whereas power in this scenario is exported from Norway 75% of the year. The minor shift in curves in 2040 - Wind&Solar underlines the fact that the distributional effects of the UK-N cable is less visible.

Further, the usage of the UK-N cable varies greatly depending on the simulated scenario. In 2040 - CP, the cable is mostly used for exports from NO5 to UK-N as means of displacing more expensive thermal power in UK-N, but also for transiting purposes further south towards UK-M. The latter will be discussed more thoroughly later. The steepness of the duration curve is, however, of great interest. Especially for the 2040 - CP scenario it can be clearly seen that, once the cable is used for imports to NO5, the magnitude of the transferred power is mostly close to rated capacity of 1 400 MW. This is believed to coincide with periods where the power price in UK-N is dropping rapidly. This is typically when there is a major unbalance between large VRES production and low demand. Later sections will handle this topic more in-depth.

Lastly, both the duration curves are seen to inhibit a couple of the properties that was seen from the duration curve presented by NVE in Section 3.1.2. The 2040 - CP curve reflects to best degree the shape of the NVE curve as it remains somewhat close to the rated values for most of the time. The 2040 - Wind&Solar curve intersects the x-axis in the same range (60-80%) as what was presented by NVE.

8.2.2 Transiting effects

The distributional effects of the UK-N cable regarding power exchange differs significantly between the two scenarios. Accordingly, this has transiting effects throughout the simulated system regarding changes in power production mix (as seen in Figure 7.1 and 7.2). As denoted, Norwegian exports on existing interconnections drops following the UK-N cable. In 2040 - CP this correlates to the increased power production in countries connected to Norway, apart from UK. Interestingly, the country where power production increases the most is actually seen to be Poland! Results from power flow tracing (Table 7.4) show that almost 4/5 of the increased production is because less power stemming from Norway, Sweden and Denmark is reaching Poland. In 2040 - Wind&Solar, however, most nodes reduce their production following the implementation of the UK-N cable. The reductions are greatest in Germany, France and Italy. In the case of France, PFT shows that there is a slight increase in power stemming from the UK consumed in France, thus contributing to lower domestic production in France. Evidently, both scenarios show that the UK-N cable has a significant impact on power production elsewhere in the power grid.

Lastly, as described in the scenario building (Chapter 6), in the simulations without the UK-N cable, the interconnection between UK-S and France was strengthened with 1 400 MW. As seen from the results however, this alteration in the grid did not have any significant effect on the power trade in the south of UK. That is to say, in both scenarios without the UK-N cable the maximum power transfer remained smaller than the original capacity of 12600 MW. Combined with the fact that the power transfer between UK-S and France is partly irrelevant for most of the results, the alteration of the UK-S - France connection has been omitted from the rest of the discussion.

8.2.3 Quasi-PFT compared to PFT

This subsection will give a preliminary demonstration of the transiting effects found on the path Norway - through the UK-N cable and node UK-N - towards NI and UK-M. This can be done by means of quasi-PFT, where power production is adjusted for import and export values, as explained in Section 4.2.

Firstly power balance and exchange of node UK-N will be investigated. As a matter of fact, Table 7.3 showed that UK-N is experiencing a net power surplus in both scenarios. This means that UK-N must be a net exporter of power in order to maintain balance between domestic power production and consumption. The latter can be readily seen in Figures 7.4 and 7.6. An interesting observation here is that the introduction of the UK-N cable increases the total export from UK-N of around 6 TWh in both scenarios (see Appendix 9.3.1 for exact values). From this, exports to Norway accounts for less than 1 TWh. Taking into account the previously stated fact that there is a net power surplus in UK-N, means that there are undoubtedly major transit flows from NO5, through UK-N towards NI and UK-M. Figure 7.15a shows the calculations done in order to establish a quantitative measure of the transit flows from NO5. From the figure, one can see that around 2 TWh is calculated to flow from NO5 to UK-M. This accounts for approximately 30% and 50% of the power export from NO5 to UK-N in 2040 - CP and 2040 - Wind%Solar, respectively.

The difference in results found between quasi-PFT and MRIO PFT is first and foremost due to the fact that the quasi-PFT accounts for the year as a whole. The power flow tracing algorithm, however, calculates the power flows hour by hour, hence giving a much more nuanced picture of how the power flows in the grid. Summing over all hours of the year instead of using yearly average thus gives a more correct picture of the actual power flows. That being said, the closer the percentage of hourly import to a node from another is the percentage of yearly-average import, the more correct will the results from quasi-PFT become. This also explains why the deviation in results between quasi-PFT and MRIO PFT is greater for path NO5 - NI than NO5 - UK-M. On general basis, less power is exported from UK-N to NI than from UK-N to UK-M. For both NI and UK-M there might be periods with little or much power imports, but as the imports in NI are of smaller scale than in UK-M, the relative change will be greater. Thus will percentage hourly import to NI more often deviate from the yearly-average yielding a less correct result. Nonetheless, the fairly fast and simple calculation methodology of quasi-PFT makes it into a valuable tool for outlining potential transit flows.

8.3 CO_2 emission assessment

There are various aspects to grasp within the discussion of CO_2 emissions and CO_2 allocation. The results from the EMPS simulation, alongside the environmental assessment of the North Connect cable presented in Section 3.1.3, both relates emissions to domestic power generation. The power generation sector is undoubtedly the main source of carbon emissions in a power system, as emissions associated with transmission and consumption are negligible. Nevertheless, power generation is driven by demand, implying that electricity consumption could be considered as the primary cause of carbon emissions. In the light of this, the following discussion will establish a platform for comparison of CO_2 emissions from a producer- and consumer-point-of-view.

Firstly, the overall CO_2 savings will be studied. The figures from Section 7.4 shows that the UK-N cable brings a net reduction in CO_2 emissions for both scenarios. The magnitude of the savings do, however, differ quite a lot depending on the simulated scenario and by way of allocating CO_2 emissions. The smallest saving is found in 2040 - CP, where increased winter emissions more or less neutralizes savings during summer! The savings in domestic produced CO_2 emissions are 0,05 Mtons (0,008% reduction from the simulation without the UK-N cable). Assuming the same annual carbon emissions from passenger vehicles as was presented in Chapter "Review of previous analyses" 3, the savings is equivalent to the emissions of 25 000 passenger vehicles. On the other hand, in 2040 - Wind&Solar, the immediate environmental benefit due to the UK-N cable is seen to be around 25 times greater than that of 2040 - CP. That is to say, the overall savings are of around 1,3 Mtons (0,2% reduction from the simulation without the UK-N cable). This equals emissions from around 650 000 passenger vehicles annually.

Secondly, the environmental distributional effects regarding nodes interconnected to Norway is studied. In 2040 - CP, the distributional effects in terms of power flow have already been presented as quite clear. This becomes even more evident when studying CO_2 emissions. The savings are in UK alone of around 0,9 Mton. It shall be mentioned that this is approximately half the amount of what was presented by the NC Project group in Chapter 3. These savings are, however, largely offset by increased emissions in other countries connected to Norway. Germany, being the biggest importer of Norwegian hydropower, do also increase its CO_2 emissions the most. The CO_2 emissions increase the most during winter. In this period thermal power plants have to cover a larger share of the high consumption in Germany. In 2040 - Wind&Solar, however, the results from Section 7.3 show that the power exchange between Norway and neighbouring countries remains relatively stable. Evidently, the environmental distributional effects following the UK-N cable are quite different from those in 2040 - CP. In fact, the domestic produced CO_2 emissions in Germany do actually reduce during summer when implementing the UK-N cable!

Thirdly, transiting effects elsewhere in the power grid affecting CO_2 emissions is investigated. In 2040 - CP, a major point of interest was the fact that Poland increases its production notably following the UK-N cable. As the power plant park of Poland is mainly dominated by coal, this implies a major increase in domestic CO_2 emissions. Together with Germany, they form the main reason why the CO_2 savings in UK are more or less neutralized for the whole system in 2040 - CP. On the other hand, in 2040 - Wind&Solar, multiple countries reduce their thermal power production giving major CO_2 savings also outside the UK. Poland does also in this scenario increase domestic CO_2 emissions, although to a much smaller degree than in 2040 - CP.

Further, Section 7.5.3 compared CO_2 emissions related to domestic production and domestic consumption. In 2040 - CP, one can in general see that the distributional effects from the UK-N cable tend to be even stronger when using power flow tracing as means of CO_2 allocation. That is to say, the savings in UK are greater and the increased emissions in neighbouring countries are also greater from a consumption perspective. Consequently, summing up for the countries connected to Norway, the net savings turns out to be down to zero! In 2040 - Wind&Solar, on the other hand, the distributional effects seen from a consumption perspective is rather interesting. In fact, the CO_2 emissions created by German consumption do reduce during summer following the UK-N cable! There might be multiple reasons for this. The power flow tracing shows that the implementation of the UK-N cable does increase the contribution of power from UK to Germany slightly. Oppositely do Norwegian exports to Germany drop following the UK-N cable, neutralizing the increased British VRES contribution. Investigating further possible reasons is considered unneeded in this context. All in all, do the net carbon emission savings for neighbouring countries to Norway become somewhat similar seen from both a producing and consuming perspective.

Finally, the discussion is emphasizing calculated CO_2 intensities found in domestic electricity mixes. Figure 7.21 shows that in 2040 - CP, the CO_2 intensity in UK drops throughout the year following the UK-N cable. This is due to the fact that Norwegian hydropower displaces thermal power. In the case of Norway, one could expect the opposite to happen. However, the UK-N cable has no effect on the Norwegian CO_2 intensity during summer and gives only a slight increase during winter. As already presented, this is because the cable is mostly used for exports from NO5 to UK-N in 2040 - CP. In 2040 - Wind&Solar, on the other hand, the power exchange is more balanced, especially during winter. As the power system in UK is mostly dominated by VRES production in this scenario, the Norwegian CO_2 intensity remains small independent of the implementation UK-N cable. Overall, one can see that the CO_2 intensity of UK in 2040 - Wind&Solar has become the same order as that of UK-N in 2040 - CP. Interestingly, the UK-N cable brings a downwards shift in CO_2 intensity level for UK also in this scenario, nonetheless not as big as that seen of 2040 - CP. The effect is notably strong during summer when wind power production tends to reduce. The low CO_2 intensity seen during spring and autumn in UK is caused by increasing solar production and a relatively high wind power production. The latter decreases during summer and thus lifting the domestic CO_2 intensity slightly.

Summing up, the results from the assessment of CO_2 emissions underpins the importance of expanding system borders when studying an alteration of the power grid. The 2040 - CP simulations show that even though an increased interconnection capacity towards the UK yields lower local emissions there, emissions can raise correspondingly other places in the system. 2040 - Wind&Solar, on the other hand, showed that the UK-N cable gives reduced emissions at the point of connection as well as in other parts of the system! Hence, domestic power pool mixes and capacities turns out to heavily influence the distributional and transiting effects of a new cable.

8.4 Power prices

In order to stitch together the discussion of power price levels with what was presented in Section 2.2.4, the VRES and hydropower production alongside power exchange through the UK-N cable will be emphasised. Results regarding transit effects found by means of power flow tracing will also be studied. There are certainly other factors that affect the power prices as well, amongst them; costs of thermal power production. The latter will nonetheless be omitted from this discussion as it is considered less relevant in the context of this thesis.

To begin with, the development of the power price levels vary significantly between the two scenarios. In the 2040 - CP scenario, Figure 7.27 shows that the power prices are in the same order of magnitude throughout the winter for UK-N and NO5. The implementation of the UK-N cable does to negligible degree affect the power prices during this season. This is mostly due to the high demand and limited hydro production. Hence the net export to UK-N is small, yielding a smaller shift in domestic power price. During the summer-half, however, Norwegian power prices drop significantly following the increased seasonal hydropower production. The large power surplus in NO5 (Table 7.3) makes net export to UK-N increase (Figure 7.5). Clearly, the effect on Norwegian power prices are immediate. Table 7.11 shows that the UK-N cable leads to a 4,5 €/MWh increase in the NO5 price level during summer. This has an important effect as the chance for price collapse during summer reduces! Moreover, given a time span over the year, NO5 experience an average increased power price of 2,5 €/MWh, while the average power price increases with 2,2 €/MWh (3,5%) in Norway as a whole. This confirms the results presented in Section 3.1.2 where NVE concluded with a price increase of 1-3 €/MWh.

On the other hand, the effect the UK-N cable has on the power prices differs considerably in scenario 2040 - Wind&Solar. First of all, the price level in UK-N is significantly lower than in 2040 - CP, and consequently also much lower than the Norwegian power price during autumn, winter and spring. This has to do with the great net power surplus in UK-N in 2040 - Wind&Solar, as seen in Figure 7.7 and Table 7.3. The low marginal costs associated with VRES production and the corresponding merit order effect, presented in Section 2.2.4, are thus retrievable from the simulation results. Secondly, the UK-N cable contributes to increase prices in UK-N during winter due to bottleneck trading. Thirdly, during summer, VRES production reduces while hydro production in NO5 increases. That being the case inverts the relationship between power prices in UK-N and NO5. This is readily seen in Figure 7.33, where also Norwegian power prices are yet again shifted upwards due to high net export. Fourthly, the significant VRES production capacity in UK-N has a contagion effect on domestic UK power price level. Figure 7.32 shows that the in power price varies from 40 €/MWh up to 70 €/MWh. This implies that the price level in UK-N varies in the same order of magnitude as NO5, although with an inverted intra-year development.

Table 7.12 shows that the shift in price level in NO5 is smaller in the 2040 - Wind&Solar scenario. During summer, prices are seen to increase with 1,2 €/MWh, while the average over the year is 0,6 €/MWh (1%). This is since there is less net export from NO5 to UK-N in 2040 - Wind&Solar, as seen from Figure 7.12. Accordingly do the change in water-values of Norwegian hydropower become smaller than in 2040 - CP, which will be further discussed in the next paragraph.

Interestingly, it turns out that domestic power production capacity does to large degree affect to what extent prices are shifted upwards when implementing the UK-N cable. Non-surprisingly, Norwegian power increases its value during summer in both scenarios. This is because that Norwegian water values are strongly related to the marginal cost of thermal production in neighbouring nodes [60]. As the alternative to hydro production is imports from UK-N, where thermal power is the marginal generation facility, Norwegian water values will increase. The upwards shift in price level can also be seen for UK-N during winter in 2040 - Wind&Solar.

More surprisingly, the asymmetric distributional effect regarding devaluation of power in high-price areas is not clearly seen (see Section 2.2.4). That is to say, the energy price in UK-N in 2040 - CP remains somewhat equal despite the introduction of the UK-N cable. The reason behind this does also have to do with the cost of thermal power generation in UK-N. The thermal power pool in UK-N is dominated by gas, and there is little variation in the technologies utilized. Hence, the power plant supplying marginal demand during summer in UK-N will yield more or less the same price formation regardless of the UK-N cable. Overall, this has an important implication as the consumer surplus on the high-price side of the UK-N cable might not be as noteworthy as first expected.

The results regarding difference in power price between UK-N and Norway are as expected. Both in 2040 - CP and 2040 - Wind&Solar there is a clear tendency that the UK-N cable contribute to mitigate the variation in energy price on each end of the cable. Indeed, power prices tend to converge when nodes are interconnected [9]. The effect is best seen in times where there are major distinctions in price level between the two nodes, as increased price differences stimulate power exchange by means of bottleneck trading (see Section 2.2.4).

Ultimately, the significance of difference in power price as driving force for power exchange is studied. This is easiest seen in 2040 - Wind&Solar where the power price variation between the two nodes has the magnitude of at least 20 €/MWh for a major part of the year. Figure 7.34 shows how the direction of power flow on the UK-N cable changes from UK-N being net exporter during winter to NO5 being net exporter during summer. This corresponds well with the fact that prices are lowest in UK-N during winter and NO5 during summer. More interesting, however, is the fact that the magnitude of power export is considerably larger in the case where NO5 function as net exporter compared to UK-N as net exporter. Similarly to what was discussed in Section 7.3, this is due to the demand of balancing power in short periods of low VRES production and hydropower transiting through UK-N.

There are several interesting points regarding the study of intra-week fluctuations in power exchange and prices in UK-N (Figures 7.30 and 7.35). Sections 2.2.1 and 2.2.4 discuss how a typical property of systems dominated by VRES plants is that the production varies more than in conventional power plants. The varying power prices become all more apparent when plotted against the more stable Norwegian hydropower prices. Such variation in power prices could stimulate for, amongst others, demand-side assets that can change the aggregate load profiles. This could yield consumption flexibility as a process for dispatching and balancing.

In both figures showing the intra-week development of power exchange there are at some times a non-intuitive relationship between the direction of power exchange and difference in prices between UK-N and NO5. That is to say, UK-N is importing power from NO5 even though the power prices in NO5 is greater than in UK-N. This is mostly due to corresponding price level seen in UK-M and becomes particularly evident in the 2040 - Wind&Solar scenario. Here, one can see from Figure 7.35 that the periods where UK-N is importing expensive power from NO5 coincides with an even greater power price in UK-M. Hence, it is tempting to believe that some of the exported power from NO5 to UK-N during these periods is transiting through UK-N towards UK-M. The results from power flow tracing supports this idea as the power traced back to NO5 in the electricity mix of UK-M increases significantly during these periods! This further explains why the UK-N cable is mainly used for exporting purposes, as seen in the duration curves. Norwegian power is not necessarily consumed in UK-N but rather transiting south-/westwards.

8.5 Uncertainties and limitations

General

Discussing uncertainties can be done from different perspectives. Sources of error and miscalculations can possibly be found in various parts of a study, and thereby also have up-/downstream impact on other parts of the study. In general, uncertainties could be divided into two main groups; errors in scenario build-up and errors in modelling of power system. These will be further investigated in the forthcoming sections.

Scenario construction

One could argue that the main backdrop for writing this thesis is the common carbon mitigation initiative and limiting climate changes. Accordingly, the overall environmental policy and willingness to create a sustainable future society is crucial. Various RES-targets has been set, amongst them the worldwide Paris Agreement [91] and EU's 2050 Carbon Neutrality [21], showing the ambitions society is having towards a renewable future. However, meeting these targets is dependent on a number of factors. Firstly, an uneven economical development in EU and the rest of the world can complicate important cross-border cooperation [101]. Hence, this could possibly lead to differences in electricity demand and thus affect price levels. As presented earlier, more fluctuations in power prices will typically increase the amplitude and direction of power flow in interconnection cables. Moreover, economic and social crises like the financial crisis in 2008 and the on-going corona epidemic have can create obstacles for implementation of CO_2 reducing policies [101]. Furthermore, technological development may have considerable influence on power prices and CO_2 emissions. Innovative solutions and technology affect both profitability and sustainability of projects, possibly making the scenario foundation from Chapter 6 out-dated.

Modelling of power system

The initial discussion in Section 8.1 about the static energy production from renewable resources and some thermal power plants has important implications for the analysis done in this thesis. Chapter 2 "Literature Review" presented how interconnecting resources can stimulate increased exploitation of renewable energy in terms of wind and solar irradiation. The fact that VRES production is constant in the EMPS model, despite the alteration of the grid with the UK-N cable, undermines some of the effects one could expect to see from the UK-N cable. This accounts first and foremost to the potential increased VRES production in UK-N where more wind and solar power could be produced and exported rather than curtailed. Furthermore, some amount of hydro production is likewise explicitly given in the simulations, which makes it more challenging to pinpoint periods where hydropower seemingly is used for balancing purposes. Under these circumstances, the results concerning carbon emission calculations will indeed be affected. Put in other words, the changes in carbon emissions seen in UK following the UK-N cable are due to the introduction of more power coming from Norway, making the constant amount of VRES displace marginal thermal power. Conversely, with a dynamic VRES production one could expect the carbon emissions to drop even more as the UK-N cable could give incentive for a greater share of VRES in the electricity mix.

Secondly, the CO_2 intensities used for the various power plants are solely based upon point-emissions - carbon emissions associated with the power production. This is a common practice in many environmental assessment studies regarding power systems. It can, however, be argued that construction, maintenance and decommissioning of power plants, as well as fuel extraction are processes with considerable carbon emissions. Thus in a life cycle analysis, the results found in this thesis represent only one out of several aspects when assessing lifecycle emissions of the simulated system.

Thirdly, the fact that coal-fueled thermal power plants are not simulated with carbon capture-and-storage (CCS) should be mentioned. This follows from the scenario build-up where REF2016 does not assume this modern technology to be mature for coal plants before in 2050. An earlier introduction of CCS in coal-fueled plants would undoubtedly influence the results regarding distributional effects and change in CO_2 emissions.

Further, the EMPS model utilized in this thesis has been developed over some decades, as mentioned in Section 5.1. That being said, this does not imply that the model is without imperfections. The model is in fact an optimization model for a hydro-thermal system, which means that results deviating from real-life values can be due to missing and/or over-simplified constraints in the power system. With this in mind, one could, e.g., look at the probability of failures and reduced availability in the power system. In this thesis, the model has not accounted for unexpected events. In fact, this is too optimistic as it will be failures from time to time. Such failures are believed to affect significantly the electricity price levels and thereby also the nodal power exchange. Furthermore, both financial incentives, such as interconnection cables being used as balancing agents and technical aspects like directions for ramping of power in cables, are not accounted for in the model. Moreover, installed capacities for production and transmission might be out-dated. Such simplifications underpins the importance of being critical when analyzing the results.

Lastly, when simulating the power grid, constraints due to laws of electricity are usually modelled in two ways; either with a linearized power flow model or a transport model [89]. Since the intended use of the model in this thesis is to provide energy flows and CO_2 impacts of an interconnector between Norway and UK on a European geographic scale, a transport model is considered to be the most appropriate. The choice of utilizing the EMPS model - being a transport model - brings along some limitations. One of them is the study of USFs (see Section 4.3. The EMPS model divides the network into aggregated nodes and allocates power flows where there is free capacity, not taking into account laws of electricity. Hence, the study of USFs becomes out-of-scope for this research.

8.5.1 Power flow tracing

There are room for improvements regarding the power flow tracing algorithm. Undoubtedly, the tracing results should be validated. However, this is easier said than done, as PFT is a field of study which is not yet significantly mature. Hence there exist few-to-none PFT modules that of today is available for the public. The quasi-PFT conducted in this thesis for the path NO5 - UK-N - UK-M showed some consistency towards the PFT results. This is, however, by far any validation of the tracing results and should be taken with a pinch of salt. Moreover, the fact that the simulations from the EMPS model tends to result in a total production which deviates slightly from total consumption is not accounted for in the power tracing module. That is to say, the tracing algorithm is solely considering nodal consumption for each time step. Furthermore, there was found a source of error in terms of numeric float precision in the computations. Lastly, there is a subsequent need for optimising the code and making it more computationally efficient.

Regarding the CO_2 emission calculations, it is observed an inconsistency between total CO_2 emissions seen from a producing and consuming point-of-view. As the EMPS model simulates a closed system, the total amount of carbon emissions should have been the same when allocating CO_2 from production and consumption. The results in Section 7.5 showed that the overall CO_2 emissions from PFT increase with 1‰ and 0,2‰ in 2040 - CP and 2040 - Wind&Solar respectively. Thorough investigation of the implementation of the PFT module revealed that this error was likely caused by two factors. Firstly, as mentioned, the slight deviation in total production and total consumption from the EMPS model is not accounted for in the power tracing module. Consequently, this can give a deviation in calculated CO_2 emissions from PFT compared to the results from the EMPS model. The second reason is due to the erroneous numeric float precision in the computations. Correcting the latter error is believed to be a fairly time-consuming process as it requires a step-by-step approach keeping track of multiple variables with high decimal precision. All in all, for the purpose of this thesis the deviations in calculated CO_2 emissions was therefore considered to be acceptable when weighing workload towards slightly more precise results.

Price-variation

The price fluctuations of the power system studied are crucial for the amount and direction of nodal power exchange. Hence, it is interesting to see how the price variations from the model compares to historical price variations. The intraday price variations for the simulated year of 2040 - CP for area NO5, and historical values for year 2019, are given in Appendix 9.3.1. Seen from these values, it is clear that the model tends to operate with much narrower price ranges than what is found historically. On the other hand, the standard deviation of the price data is smaller for the historical values compared to that of the EMPS model. There may be several reasons for these deviations. First of all is the EMPS simulation done for 6 hour periods while the historical price values are hourly based. Moreover, model inputs to the EMPS like costs, losses and other assumptions might be erroneous. Real-life market imperfections are not accounted for in the EMPS, but do undoubtedly have an impact on the power prices. All in all, model elements and assumptions do affect the development of power price levels. It is therefore important to bear in mind that these assumptions and limitations consequently have a significant impact on power flows and thus environmental properties of the power system.

Chapter 9

Concluding Remarks

This thesis gives a preliminary investigation, to the extent it was feasible in the limited time frame, into some of the impacts a new, generic, cable from Western Norway to the North of UK would have on the power system. Consequences regarding power exchange, power prices and changes in CO_2 emissions in Norway, the UK and Europe as a whole are emphasised. The assessment is conducted by means of two scenarios; one is intended to reflect the European energy outlook presented by the EU in 2016 (REF2016 [22]) and the other extends this scenario by increasing the share of VRES and power surplus in Norway, Sweden and the UK. These two scenarios are simulated with and without the cable from Norway to UK-N utilizing the EMPS model. The quantitative analysis performed are based upon the results from these simulations. Combined with qualitative discussions, this lays the foundation for the assessment conducted in this thesis.

9.1 Summary of Results

A detailed discussion of the results obtained from the scenario simulations, and some of their implications, are presented in chapter 8 "Discussions". A brief summary will therefore be presented here:

- The UK-N cable brings environmental benefits in terms of reduced CO_2 emissions in both scenarios. In the whole simulated system the CO_2 emissions reduce with 0,05 Mton and 1,3 Mton in 2040 - Current Policy and 2040 - Wind&Solar, respectively.

- The reductions in domestically produced CO_2 emissions are not evenly distributed amongst the various nodes in the system. 2040 - Current Policy showed that the UK was the only place of reduced CO_2 emissions. While for other countries interconnected to Norway, emissions related to domestic production increase. In 2040 - Wind&Solar, however, the savings in the UK are smaller, meanwhile multiple other countries also reduce their emissions.

- The power flow tracing show in 2040 - Current Policy an amplified environmental effect of the UK-N cable. In other words, both the savings in UK and the increased domestic emissions in other countries are of larger magnitude when allocating CO_2 from a consuming point-of-view. Likewise in 2040 - Wind&Solar, the reduction in emissions in UK is greater when allocating CO_2 emissions to consumption rather than production.

- The CO_2 intensity in the consumed electricity mix in UK drops significantly, especially during summer, when implementing the UK-N cable. The increase in Norwegian CO_2 intensity, however, is negligible.

- The power prices in Norway are found to raise due to the UK-N cable. The increase, for 2040 - Current Policy and 2040 - Wind&Solar, is on average 2,2 €/MWh (3,5%) and 0,6 €/MWh (1%), respectively.

- The net power export from Norway increases in both scenarios. Due to distributional effects, however, do the net export on existing interconnections drop following the UK-N cable.

9.2 Future Work

Section 8.5 presented some of the uncertainties and limitations in this study.

An obvious issue that emerges to the fore is the choice of utilizing the EMPS for simulation purposes. One of the drawbacks with this model is that VRES production is a static exogenous variable. That is to say, the VRES production remains constant when simulating with and without the UK-N cable. This has undoubtedly multiple consequences regarding CO_2 emissions, power flows and prices. Hence, to clearer see the effects of a new interconnection, it would be beneficial to operate with a simulation model that facilitates wind and solar production as dynamic endogenous variables. Secondly, the fact that the EMPS is a transport model brings along some limitations, amongst them not facilitating the study of USFs. All in all, for future research about the effects of a new interconnection, considerations regarding different model trade-offs should be taken into account.

Another issue is the scenario construction. One could argue that an important premise for obtaining probable and realistic simulation results, is that the scenarios to some degree reflect the state-of-the-art power market seen in the future. Thus firstly, the scenario build-up is reckoned to mostly be based upon reports from 2016. The TYNDP2016 report, e.g., which lays the foundation for the simulated interconnection capacities, has been updated with TYNDP2018. Updating the scenario building was considered to be too time-consuming and of minor interest, as it did not bring any new interconnection capacity to Norway compared to that of 2016. Secondly, there are examples where the REF2016 is not up-to-date regarding energy policy in different countries. In Germany there has been set target of phasing-out coal by 2038 as a part of their infamous "Energiewende" [38]. The REF2016 scenario, however, states that approximately 1/4 of Germany's gross electricity production in 2040 is coming from coal-fired power plants. All in all, a more up-to-date energy system could be beneficial. This is, however, indeed a trade-off between time used for tuning simulation parameters and the requirement for realistic simulation results.

Lastly, the conduction of this thesis shows that it might be somewhat challenging to analyze the power flow tracing results as there are multiple variables that all affect each other. Up- and downstream distributional effects in the power system are a difficult field of study due to the complexity of the power grid. As with most other fields of science - acquiring simulated results is one step - yet fully understanding the mechanisms behind is a long journey. Consequently, pointing out sources of error is complicated and time-consuming. Moreover, the power flow tracing results can hardly be verified as there exist few-to-none publicly available PFT implementations matching the one used in this thesis. The latter thus questions the validity of the results and underlines the fact that applications of power flow tracing is still a field of study where more research is warranted. Altogether, however, a framework for power flow tracing has been created. The benefits of applying PFT to a practical European power system model can hopefully inspire to further dedicated research within this field at the Department of Electric Power Engineering at NTNU!

9.3 Reflections about the study

What implications do the results in this thesis so have for policymaking and the common goal of carbon mitigation?

First of all, this thesis demonstrate the importance of expanding system borders when studying effects of a topological alteration of the power grid. The modern power system is severely complex and intricate, and an alteration in topology in one part of the grid can have major, potentially unexpected, impacts other places in the system. Indeed do the scenario analyses show that the UK reduces domestic CO_2 emissions following the UK-N cable. However, depending on how the power system develops, this carbon mitigation can to large degree be offset by increasing carbon emissions elsewhere! Consequently, for the purpose of studying effects of power grid investments, it can be argued that it is insufficient and inaccurate with an approach that only considers an isolated system containing the immediate parties affected by the alterations.

Secondly, even though a country like Norway is almost solely based upon renewable energy production, it does not mean that the country is free of blame for carbon emissions. Power consumption stimulates power generation, and accordingly did the power flow tracing allocate CO_2 emissions to Norwegian consumption as well.

Thirdly, the power flow tracing shows that the distributional effects following the UK-N cable are in many countries even stronger when allocating CO_2 emissions from a consuming pint-of-view. As the carbon intensity of domestic consumption increases, so must the amount of consumption decrease in order to maintain a constant carbon emission level.

Environmental policymaking seen nowadays is getting more and more ambitious. National action plans for sustainable development typically assign goals for future domestic CO_2 emissions (see e.g., [20], [64], [14]) as a way of measuring progress. This thesis shows, however, that the assessment of CO_2 emissions heavily depends on the system boundaries. Accordingly, domestic carbon emissions are to large degree also affected by the policymaking elsewhere in the power system. Hence, cross-border cooperation is indeed essential for reaching carbon obligations and creating the sustainable society of tomorrow.

9.3.1 Recognizing findings while appreciating uncertainties

Mathematical models will hardly fully represent the case subjected to study when analyzing real-life mechanisms. Due to the vast complexity of real-life systems, these models are subjected to a certain level of simplification. Inputs and outputs of such models are stylized quantifications strongly affected by the researcher's approach of modelling. Applying such a model to predict future scenarios involves yet another degree of uncertainty as no-one knows how the future will unfold. That being said, even though explicit and implicit assumptions might bring along errors, this does not imply that the results of the model study are worthless [101]. Put in other words, important findings contribute to shed light on the topic of study and provides a more nuanced picture of the possible outcomes of future real-life decisions.

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Appendices

Appendix A - Production mixes

Area	Gas	Oil	Coal	Bio	Nuclear	Diverse	Other RES	Hydro	PV	Wind	ton CO2	Demand
AL	-25,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-8414,6	0,0
AT	-35,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-11542,4	0,0
BA	-2,9	0,0	-2,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-4481,5	0,0
BE	-213,8	0,0	0,1	0,2	0,0	0,0	0,0	0,0	0,0	0,0	-79872,4	0,0
BG	-5,9	0,0	-5,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-8519,2	0,0
CH	0,0	0,0	0,0	0,0	0,2	0,0	0,1	0,0	0,0	0,0	16,9	0,0
CZ	-24,5	0,0	-2,7	0,0	0,5	0,0	0,0	0,0	0,0	0,0	-13059,6	0,0
DE	-484,8	0,2	46,3	1,1	0,0	0,2	-0,2	0,0	0,0	0,0	-131809,1	0,0
DK-E	-7,5	0,0	0,9	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	-1744,2	0,0
DK-W	-12,0	0,0	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	0,0	-4176,4	0,0
EE	9,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3173,2	0,0
ES	-224,7	0,4	14,2	4,7	8,4	0,0	0,0	0,0	0,0	0,0	-58187,7	0,0
FI	5,1	0,0	30,4	0,9	8,0	0,0	0,0	0,0	0,0	0,0	31145,0	0,0
FR	-797,5	0,1	55,4	11,5	128,4	0,0	0,5	0,0	0,0	0,0	-233997,8	0,0
GR	-24,5	0,0	-4,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-14456,6	0,0
HR	-9,9	0,0	-5,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-9498,9	0,0
HU	-21,4	0,0	0,0	0,0	0,4	0,0	0,0	0,0	0,0	0,0	-7076,6	0,0
IE	-171,7	0,0	-20,1	-2,8	0,0	0,0	-0,2	0,0	0,0	0,0	-84405,6	0,0
IT	-600,2	0,0	-2,7	0,5	0,0	0,0	0,1	0,0	0,0	0,0	-206315,4	0,0
LT	3,6	0,0	0,0	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	1169,8	0,0
LU	-14,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-5110,0	0,0
LV	5,8	0,0	0,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2598,1	0,0
ME	0,0	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-352,6	0,0
MK	-8,5	0,0	-4,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-8015,5	0,0
NI	-81,7	0,0	0,0	0,0	0,0	0,0	-0,6	0,0	0,0	0,0	-29126,6	0,0
NL	-202,0	0,0	10,0	0,3	0,0	0,0	0,0	0,0	0,0	0,0	-58737,4	0,0
NO1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO2	0,0	0,0	0,0	6,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
PL	1,6	0,0	65,1	-0,1	0,1	0,0	0,0	0,0	0,0	0,0	66635,1	0,0
PT	-13,8	0,0	0,0	0,3	0,0	0,0	0,2	0,0	0,0	0,0	-4375,9	0,0
RO	-15,0	0,0	-2,8	0,0	0,2	0,0	0,0	0,0	0,0	0,0	-8631,9	0,0
RS	-56,3	0,0	-2,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-23407,2	0,0
SE1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
SE2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
SE3	2,2	0,0	1,6	22,8	64,9	0,1	13,3	0,0	0,0	0,0	2339,7	0,0
SE4	5,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1821,4	0,0
SI	-11,4	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-4298,8	0,0
SK	11,0	0,0	0,8	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4762,8	0,0
UK-N	-48,3	0,0	0,0	159,9	268,1	0,1	570,0	0,0	0,0	0,0	-18413,2	0,0
UK-M	-779,7	0,0	0,0	-34,1	-81,6	0,0	-10,9	0,0	0,0	0,0	-256238,0	0,0
UK-N	-410,4	0,0	0,0	0,0	-57,4	0,0	-7,0	0,0	0,0	0,0	-148901,7	0,0
sum	-4258,4	0,7	173,2	171,7	339,9	0,4	565,1	0,0	0,0	0,0	-1329504,9	0,0

Figure 9.1: 2040 - CP: Change in production mix following the UK-N cable.

Area	Gas	Oil	Coal	Bio	Nuclear	Diverse	Other RES	Hydro	PV	Wind	ton CO_2	Demand
AL	-0,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-177,9	0,0
AT	-2,4	0,1	0,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	436,5	0,0
BA	0,0	0,0	3,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4161,3	0,0
BE	-130,3	0,0	0,2	0,2	0,0	0,0	0,0	0,0	0,0	0,0	-47268,9	0,0
BG	-2,7	0,0	6,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4806,1	0,0
CH	0,7	0,0	0,0	0,0	-0,2	0,0	0,0	0,0	0,0	0,0	291,7	0,0
CZ	26,6	0,0	33,6	0,0	1,1	0,0	0,0	0,0	0,0	0,0	45022,1	0,0
DE	60,9	0,9	384,9	1,3	0,0	0,0	0,0	0,0	0,0	0,0	422113,0	0,0
DK-E	17,4	0,0	12,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	18436,1	0,0
DK-W	18,4	0,0	11,4	0,1	0,0	0,0	0,0	0,0	0,0	0,0	17833,8	0,0
EE	25,0	0,0	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	8515,1	0,0
ES	-186,8	0,2	5,8	0,0	-7,3	0,0	0,0	0,0	0,0	0,0	-57538,4	0,0
FI	38,0	0,1	98,2	5,2	8,3	0,0	0,0	0,0	0,0	0,0	105516,6	0,0
FR	-509,8	0,0	12,5	0,2	1,1	0,0	0,0	0,0	0,0	0,0	-170100,2	0,0
GR	-12,5	0,0	5,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1476,7	0,0
HR	-1,2	0,0	5,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4694,9	0,0
HU	-7,2	0,0	0,1	0,1	0,1	0,0	0,0	0,0	0,0	0,0	-2150,8	0,0
IE	-8,5	0,0	49,0	0,6	0,0	0,0	0,0	0,0	0,0	0,0	45995,8	0,0
IT	-332,9	0,1	13,7	1,6	0,0	0,0	0,0	0,0	0,0	0,0	-100923,5	0,0
LT	13,5	0,0	0,0	0,0	0,4	0,0	0,0	0,0	0,0	0,0	4675,2	0,0
LU	-1,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-621,9	0,0
LV	24,1	0,0	2,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	10604,9	0,0
ME	0,0	0,0	0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	543,4	0,0
MK	-3,4	0,0	2,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1210,8	0,0
NI	-67,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-23523,3	0,0
NL	15,6	0,0	69,2	0,6	0,0	0,0	0,0	0,0	0,0	0,0	74363,6	0,0
NO1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
NO5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
PL	86,1	0,5	427,9	0,1	0,0	0,0	0,0	0,0	0,0	0,0	494646,6	0,0
PT	-15,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	-5319,8	0,0
RO	-8,8	0,0	2,7	0,0	0,1	0,0	0,0	0,0	0,0	0,0	-446,1	0,0
RS	-9,4	0,0	3,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	613,6	0,0
SE1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
SE2	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
SE3	5,6	0,1	5,5	48,1	384,4	0,0	0,3	0,0	0,0	0,0	7453,7	0,0
SE4	10,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3533,8	0,0
SI	-4,2	0,0	2,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1083,8	0,0
SK	6,6	0,0	6,1	0,0	-0,1	0,0	0,0	0,0	0,0	0,0	10373,7	0,0
UK-N	-103,7	0,0	6,6	1,6	19,1	0,0	0,0	0,0	0,0	0,0	-30436,5	0,0
UK-M	-1714,7	0,0	20,0	29,2	25,9	0,0	0,0	0,0	0,0	0,0	-520507,3	0,0
UK-N	-1063,7	0,0	0,0	0,0	10,4	0,0	0,0	0,0	0,0	0,0	-378244,4	0,0
sum	-3838,5	2,4	1190,6	89,0	443,2	0,0	0,4	0,0	0,0	0,0	-48856,2	0,0

Figure 9.2: 2040 - Wind&Solar: Change in production mix following the UK-N cable.

Appendix B - Power production and surplus in Norway and Sweden

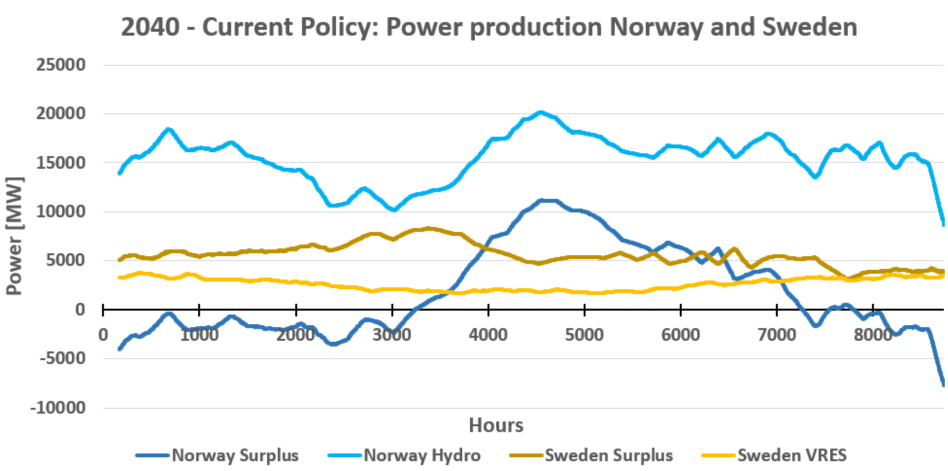

Figure 9.3: 2040 - Current Policy: Norwegian hydro production, Swedish wind and solar production alongside power surplus in both countries including the UK-N cable.

Appendix C - Power exchange

Table 9.1: 2040 - CP: Exports and import values for power exchange between Norway and neighbouring countries, as well as between UK-N and its neighbouring nodes.

With UK-N cable		
Connection	Export [GWh]	Import [GWh]
NO5 - UK-N	6 741	559
NO - SE	1 682	24 563
NO - DK	6 467	1 099
NO - DE	15 463	2 047
NO - NL	32 794	355
NO - FI	116	182
NO - UK (Excluding UK-N cable)	6796	355
NO - Abroad (Excluding UK-N cable)	33 803	28 600
UK-N - Abroad (Excluding UK-N cable)	20 031	285
Without UK-N cable		
Connection	Export [GWh]	Import [GWh]
NO5 - UK-N	0	0
NO - SE	2 822	23 320
NO - DK	7 039	1 021
NO - DE	16 580	1 916
NO - NL	3 474	333
NO - FI	127	176
NO - UK (Excluding UK-N cable)	7138	382
NO - Abroad (Excluding UK-N cable)	37 179	27 147
UK-N - Abroad (Excluding UK-N cable)	14 125	358

Table 9.2: 2040 - Wind&Solar: Exports and import values for power exchange between Norway and neighbouring countries, as well as between UK-N and its neighbouring nodes.

With UK-N cable		
Connection	Export [GWh]	Import [GWh]
NO5 - UK-N	2 903	1 126
NO - SE	3 882	18 930
NO - DK	7718	775
NO - DE	18 507	1 255
NO - NL	3 784	220
NO - FI	139	144
NO - UK (Excluding UK-N cable)	4 831	665
NO - Abroad (Excluding UK-N cable)	38 860	21 988
UK-N - Abroad (Excluding UK-N cable)	63 231	0
Without UK-N cable		
Connection	Export [GWh]	Import [GWh]
NO5 - UK-N	0	0
NO - SE	4 343	18 814
NO - DK	7 845	759
NO - DE	18 672	1 236
NO - NL	3 809	217
NO - FI	140	145
NO - UK (Excluding UK-N cable)	5 019	681
NO - Abroad (Excluding UK-N cable)	39 827	21 853
UK-N - Abroad (Excluding UK-N cable)	58 425	0

Appendix D - Power exchange Norway - Abroad

Table 9.3: Power exchange between Norway and interconnecting countries with and without the UK-N cable.

	2040 - CP		2040 - Wind&Solar	
GWh	With cable	Without cable	With cable	Without cable
Export	40 544	37 179	41 763	39 827
Change Export	9%	-	7,5%	
Import	29 159	27 147	23 114	21 853
Change Import	5%	-	6%	

Appendix E - CO_2 emissions

2040 - Current Policy	Summer			Winter			Year			
	With cable	Without cable	Change Summer	With cable	Without cable	Change Winter	With cable	Without cable	Change Year	Change [%]
UK	10 814 627	11 358 739	-544 113	10 982 598	11 367 673	-385 075	21 797 225	22 726 413	-929 188	**-4,09 %**
Norway	0	0	0	0	0	0	0	0	0	**0,00 %**
Sweden	124 833	115 774	9 058	346 279	344 350	1 929	471 111	460 124	10 987	**2,39 %**
Denmark	2 184 270	2 166 472	17 798	3 566 714	3 548 242	18 472	5 750 984	5 714 714	36 270	**0,63 %**
Germany	98 995 217	98 866 976	128 242	98 259 189	97 965 318	293 871	197 254 406	196 832 294	422 113	**0,21 %**
Netherlands	17 953 409	17 934 496	18 913	20 249 919	20 194 469	55 450	38 203 328	38 128 965	74 363	**0,20 %**
Finland	1 473 904	1 383 993	89 911	2 698 103	2 682 498	15 605	4 172 007	4 066 491	105 517	**2,59 %**
Total nodes	131 546 260	131 826 450	-280 191	136 102 801	136 102 550	252	267 649 061	267 929 000	-279 939	**-0,10 %**
Total system	289 638 747	289 910 611	-271 864	310 367 816	310 144 809	223 007	600 006 562	600 055 420	-48 857	**-0,01 %**

Figure 9.4: 2040 - Current Policy: CO_2 emissions related to power production.

2040 - Wind&Solar	Summer			Winter			Year			
	With cable	Without cable	Change	With cable	Without cable	Change	With cable	Without cable	Change	Change [%]
UK	4 080 754	4 323 707	-242 953	4 501 995	4 682 596	-180 600	8 582 749	9 006 302	-423 553	**-4,70 %**
Norway	0	0	0	0	0	0	0	0	0	**0,00 %**
Sweden	114 683	111 265	3 418	327 454	326 711	743	442 138	437 977	4 161	**0,95 %**
Denmark	2 069 954	2 077 549	-7 595	3 339 906	3 338 233	1 674	5 409 861	5 415 782	-5 921	**-0,11 %**
Germany	95 151 921	95 287 137	-135 217	93 457 235	93 453 827	3 408	188 609 155	188 740 964	-131 809	**-0,07 %**
Netherlands	17 134 623	17 176 075	-41 452	19 276 091	19 293 377	-17 286	36 410 715	36 469 452	-58 737	**-0,16 %**
Finland	1 385 212	1 361 311	23 901	2 541 690	2 534 446	7 244	3 926 901	3 895 756	31 145	**0,80 %**
Total 7 nodes	119 937 148	120 337 043	-399 896	123 444 372	123 629 190	-184 818	243 381 519	243 966 233	-584 714	**-0,24 %**
Total system	271 431 529	272 297 186	-865 657	288 492 230	288 956 077	-463 847	559 923 759	561 253 263	-1 329 504	**-0,24 %**

Figure 9.5: 2040 - Wind&Solar: CO_2 emissions related to power production.

2040 - CP	EMPS		PFT	
	Summer	Winter	Summer	Winter
UK	-544	-385	-662	-416
Norway	0	0	8	46
Sweden	9	2	8	26
Denmark	18	18	44	43
Germany	128	294	269	412
Netherlands	19	55	44	75
Finland	90	16	90	16
Sum 7 countries	-280	0	-199	202
Sum total	-272	223	-249	245

Figure 9.6: 2040 - Current Policy: Comparison CO_2 emissions from producing and consuming point-of-view.

2040 - Wind&Solar	EMPS		PFT	
	Summer	Winter	Summer	Winter
UK	-243	-181	-347	-274
Norway	0	0	-1	10
Sweden	3	1	2	4
Denmark	-8	2	-9	9
Germany	-135	3	-102	73
Netherlands	-41	-17	-36	4
Finland	24	7	24	8
Sum 7 countries	-400	-185	-469	-168
Sum total	-866	-464	-858	-456

Figure 9.7: 2040 - Wind&Solar: Comparison CO_2 emissions from producing and consuming point-of-view.

Appendix F - Power prices

Table 9.4: Standard deviation and price range for one year in node NO5. All values in €/MWh.

	2040 - CP	Historical 2019 Values
Standard deviation	10,9	8,3
Price range	59,3	103,6

Appendix G - Nodes in EMPS model

#	EMPS	Name	#	EMPS	Name
1	AL	Albania	23	ME	Montenegro
2	AT	Austria	24	MK	Macedonia
3	BA	Bosnia and	25	NI	Northern Ireland
		Herzegovina	26	NL	Netherland
4	BE	Belgium	27	NO1	Norway 1
5	BG	Bulgaria	28	NO2	Norway 2
6	CH	Switzerland	29	NO3	Norway 3
7	CZ	Czech Republic	30	NO4	Norway 4
8	DE	Germany	31	NO5	Norway 5
9	DK-E	Denmark East	32	PL	Poland
10	DK-W	Denmark West	33	PT	Portugal
11	EE	Estonia	34	RO	Romania
12	ES	Spain	35	RS	Serbia
13	FI	Finland	36	SE1	Sweden 1
14	FR	France	37	SE2	Sweden 2
15	GR	Greece	38	SE3	Sweden 3
16	HR	Croatia	39	SE4	Sweden 4
17	HU	Hungary	40	SI	Slovenia
18	IE	Ireland	41	SK	Slovakia
19	IT	Italy	42	UK-N	United Kingdom North
20	LT	Lithuania	43	UK-M	United Kingdom Middle
21	LU	Luxembourg	44	UK-S	United Kingdom South
22	LV	Latvia			

Figure 9.8: Area numbers, abbreviation and area name used in the EMPS model.

Appendix H - Hardcopy of PFT implementation

```
# -*- coding: utf-8 -*-
"""

@author: Ole Marius M. Forbord

"""

import load_data_EMPS
import load_emission_factors
import load_consumption
import MRIO_pow_flow
import pdb

#Some minor rounding errors in calculations  float_precision = 'round_trip'

def main(name_dir = None, year = 2040):
    #pdb.set_trace()
    if(name_dir is None):
        name_dir = input("Write directory you want to read from: ")

    nodes = load_data_EMPS.load_data(name_dir)

    E_fac = load_emission_factors.load_emission_factors(name_dir)

    consumption = load_consumption.load_consumption(name_dir)

    mix_country, Emissions_tot, Emissions_tech, Zone_power_exchange_total, Zone_consumption_tech, zonal_contribution =
MRIO_pow_flow.power_flow(nodes, E_fac, consumption, year, name_dir)

    return mix_country, Emissions_tot, Emissions_tech, Zone_power_exchange_total, Zone_consumption_tech,
zonal_contribution
```

```python
# -*- coding: utf-8 -*-
"""

@author: Ole Marius M. Forbord

"""

import pandas as pd
import numpy as np
import pdb
from tqdm import tqdm


def power_flow(nodes, E_fac, consumption, year = 2020, name_dir = None):

    if(name_dir is None):
        name_dir = input("Write directory you want to write to: ")

    #Various variables
    Time_steps = nodes['NO5'].index.values
    Time_steps = list(Time_steps)
    tot_hours = len(Time_steps)

    header_nodes = list(nodes['NO5'].columns)
    zones = list(nodes.keys())
    imports = list(nodes['NO5'].columns[34:])   #34 first elements describe technologies
    technology = list(nodes['NO5'].columns[:34])

    mix_country = {}
    Generation_summed_node = {}
    #Generation_summed_tech = {}
    Gen_info_weighted = {}
    zonal_contribution = {}


    #Making identity matrix with dimension [zones x zones]
    zone_identity = np.zeros((len(zones), len(zones)))
    np.fill_diagonal(zone_identity,1)

    intensity_tot = pd.DataFrame(0.0, index = Time_steps, columns = zones, dtype = float)
    intensity_tot.index.name = "[CO2 tonnes]"

    Emissions_tech = pd.DataFrame(0.0, index = Time_steps, columns = technology, dtype = float)
    Emissions_tech.index.name = "[tonCO2/GWh]"

    Emissions_tot_calc = pd.DataFrame(0.0, index = [0], columns = technology, dtype = float)
    Emissions_zone_tech_hour = {}
    Zone_power_exchange_total = {}
    Zone_consumption_tech = {}

    export_average_tech_distribution = pd.DataFrame(0.0, index = technology, columns = zones)
    export_average_tech_distribution.index.name = "[Percentage]"
    export_average_node_contribution = pd.DataFrame(0.0, index = zones, columns = zones)
    export_average_node_contribution.index.name = "[Percentage]"

    export_total_emission = pd.DataFrame(0.0, index = ["Total emissions year %d"%year], columns = zones)
    export_total_emission.index.name = "[CO2 tonnes]"

    export_average_intensity = pd.DataFrame(0.0, index = ["Average intensity year %d"%year], columns = zones)
    export_average_intensity.index.name = "[tonCO2/GWh]"
    export_nodes = {}
    control_values_nodes = pd.DataFrame(0.0, index = zones, columns = ["Control Value"])

    export_total_consumption = pd.DataFrame(0.0, index = ["Total consumption"], columns = zones)
    export_power_exchange = pd.DataFrame(0.0, index = zones, columns = zones)

    for zone in zones:
```

```
        Emissions_zone_tech_hour[zone] = pd.DataFrame(0.0, index = Time_steps, columns = technology)
        Emissions_zone_tech_hour[zone].index.name = "[CO2 tonnes]"

        zonal_contribution[zone] = pd.DataFrame(0.0, index = Time_steps, columns = zones)
        zonal_contribution[zone].index.name = "[Percentage]"



    #For every timestep!
    for h in tqdm(Time_steps):

        #pdb.set_trace()
        mix_country[h] = pd.DataFrame(index = technology, columns = zones, dtype = float)

        #Generation and imports summed togheter
        for key in nodes.keys():

            #Generation_summed_tech[key] = nodes[key].sum(axis=0) #nodes[key]: [1 x TEC]
            Generation_summed_node[key] = nodes[key].loc[h].sum() #nodes[key]: [1 x 1]

        #Making diagonal matrix
        Gen_diagonal = pd.DataFrame(0.0, index = zones, columns = zones, dtype = float) #[zones x zones]
        for key in nodes.keys():
            index = zones.index(key)
            Gen_diagonal.iat[index, index] = Generation_summed_node[key]


        #Inverse of the diagonal matrix [zones X zones]
        #Gives us the per unit production of each node based on total production
        #Dimension: [BZN x BZN]
        Gen_pu = pd.DataFrame(np.linalg.pinv(Gen_diagonal.values), index = Gen_diagonal.columns, columns =
Gen_diagonal.index, dtype = float)

        #Finds the weighted generation from each source for each zone
        for key in nodes.keys():
            Gen_info_weighted[key] = nodes[key].loc[h].multiply(Gen_pu.at[key,key]) #Dimension: nodes[key]: [1 x TEC+IMP]


# =============================================================================
#         ##COMBINING WITH IMPORT VALUES
# =============================================================================

        IMP_from_Zone = pd.DataFrame(index = imports, columns = zones, dtype = float)   #[IMP x zones]
        Gen_in_Zone = pd.DataFrame(index = technology, columns = zones, dtype = float)          #[TECH x zones]

        #Adding imports to dataframe for each node for each hour [IMP x Zones]
        for key, value in nodes.items():
            IMP_from_Zone.at[:,key] =  Gen_info_weighted[key].iloc[34:]

        #Adding generation to dataframe for each node for each hour [TECH x Zones]
        for key, value in nodes.items():
            Gen_in_Zone.at[:, key] = Gen_info_weighted[key].iloc[:34]

        #Now, we create a matrix telling us the connection between each BZN in terms of self-consumption and power exchange
        #We therefore have 1 for each bidding zone telling: We import 1 unit to ourselves. The imports from others will be given as
negative
        #1pu import indicates that all domestic production is contributing to the domestic el pool


        Zone_power_exchange = zone_identity-IMP_from_Zone #[IMP x Zone]

        #We then invert it, which will give us information on how each BZN affects the others. This shows how each BZN affects
each BZN consumption
        #(I-P_{imp})^-1
        #[Zone x IMP]
        Zone_power_exchange_total[h] = pd.DataFrame(np.linalg.pinv(Zone_power_exchange.values), index =
Zone_power_exchange.columns, columns = Zone_power_exchange.index)
```

```
        #M_{i,j}
        #[TECH x Zone]
        Zone_consumption_tech[h] = Gen_in_Zone.dot(Zone_power_exchange_total[h])
        Zone_consumption_tech[h].columns = zones


        #Storing for each zone
        for zone in zones:

            #Storing mix of power from each country
            #mix_country[h]: [TECH x ZONE]
            mix_country[h][zone] = Zone_consumption_tech[h][zone]

            for imp in zones:

                zonal_contribution[zone].at[h, imp] =
np.multiply(Zone_power_exchange_total[h].at[imp,"Imports_from_{}".format(zone)], Gen_in_Zone.loc[:, imp].sum())

            for tech in technology:

                #Multiplying each technology with respective CO2 intensity.

                Emissions_tot_calc[tech] = np.multiply(mix_country[h].at[tech, zone], E_fac[tech].at[0,'Specific CO2 intensity'])




            #Summing up for actual zone
            #REMEMBER: The values now stored in Emissions_tot are the CO2 intensity in the domestic el mix of a given node !! All
values in kg/MWh
            #[Time_steps x zones]
            intensity_tot.at[h, zone] = Emissions_tot_calc.sum(axis = 1)[0]

            #Defining emission related to technology for given time_step for given zone [CO2 tonnes]
            #[zones x time_steps x tech]
            Emissions_zone_tech_hour[zone].loc[h] = Emissions_tot_calc.iloc[0].multiply(consumption.at[h, zone])


        #Must be multiplied with with overall consumption in each respective node to make sense (will give total CO2 emissions pr
technology pr hour)
        #Overall emissions from distinct technologies
        for tech in technology:

            #Multiplying each technology with respective CO2 intensity.
            #Summing over all zones to get total CO2 emission for each technology for each hour
            #[Time_steps x tech]
            #TODO
            power_from_tech = mix_country[h].loc[tech,:].dot(consumption.loc[h,:])

            #Gives emissions from technology for given hour
            Emissions_tech.at[h,tech] = np.multiply(power_from_tech, E_fac[tech].at[0,'Specific CO2 intensity']).sum()


# ==============================================================================
#     Preparing for export to Excel
# ==============================================================================

    #Export of power distributions
    for zone in zones:
        export_nodes[zone] = pd.DataFrame(0.0, index = Time_steps, columns = technology)
        export_nodes[zone].index.name = "[Percentage]"

    #Export of power distributions
    for h in tqdm(Time_steps):
        for zone in zones:
```

```
            export_nodes[zone].loc[h] = mix_country[h].loc[:,zone]

        export_power_exchange = export_power_exchange.add(Zone_power_exchange_total[h])

    export_power_exchange = export_power_exchange.divide(len(Time_steps))

    for zone in zones:

        #Exports for power distribution excel

        #Average use of different technologies for the zones
        export_average_tech_distribution[zone] = export_nodes[zone].mean()

        #Average contribution each node has on each other
        export_average_node_contribution.loc[zone] = zonal_contribution[zone].mean(axis = 0)

        #Total consumption in each zone
        export_total_consumption[zone] = consumption.loc[:,zone].sum()

        #Co
        control_values_nodes.at[zone, ["Control Value"]] = export_nodes[zone].sum(axis = 0).sum()

        #Export for emission excel
        #consumption[zone]: [Time_steps x zone]
        export_average_intensity[zone] = intensity_tot[zone].mean()
        export_total_emission[zone] = intensity_tot[zone].dot(consumption[zone])


    export_average_node_contribution.rename(columns=lambda x: "power_from_{}".format(x), inplace = True)
# =============================================================================
#     Storing results into excel files
# =============================================================================

    with pd.ExcelWriter("{}/Power_Distributions_{}_float_precision".format(name_dir, name_dir)+".xlsx") as writer:

        comment = pd.DataFrame({"Values for each zone should be equal (or close to equal) the number of hours used in the
simulation (here: %dh)"%tot_hours})
        control_values_nodes.to_excel(writer, sheet_name = "Control_sheet")
        comment.to_excel(writer, sheet_name = "Control_sheet", header = None, index = False, startcol = 4, startrow = 4)
        export_average_tech_distribution.to_excel(writer, sheet_name = "Average_technology_use")
        export_average_node_contribution.to_excel(writer, sheet_name = "Average_zone_contribution")

        for zone in tqdm(zones):
            export_nodes[zone].to_excel(writer, sheet_name = "Power_plant_{}".format(zone))
            zonal_contribution[zone].to_excel(writer, sheet_name = "Zone_contribution_{}".format(zone))


    with pd.ExcelWriter("{}/CO2_intensity_{}_float_precision".format(name_dir, name_dir)+".xlsx") as writer:

        export_average_intensity.to_excel(writer, sheet_name= "Average_intensity")
        export_total_emission.to_excel(writer, sheet_name = "Total_emissions")
        intensity_tot.to_excel(writer, sheet_name = "Hourly_overview_nodes")
        Emissions_tech.to_excel(writer, sheet_name = "Hourly_overview_tech")

        for zone in tqdm(zones):

            Emissions_zone_tech_hour[zone].to_excel(writer, sheet_name = zone)



    return mix_country, intensity_tot, Emissions_tech, Zone_power_exchange_total, Zone_consumption_tech, zonal_contribution
```

```
# -*- coding: utf-8 -*-
"""
Created on Wed Mar 18 12:27:10 2020

@author: OleM
"""


import pandas as pd
from pandas import ExcelFile

import os
import win32com.client
import numpy as np
import pdb
from tqdm import tqdm


#os.getcwd()
#os.chdir("..") - upwards
#os.chdir("./sub_folder") - downwards
#for i,j,k in os.walk("."):
#    print(i)

def load_data(name_dir = None):

    if(name_dir is None):
        name_dir = input("Write name of directory where files are stored: ")

    #PWD = os.path.dirname(os.path.abspath(__file__))
    namelist = ['AL', 'AT', 'BA', 'BE', 'BG', 'CH', 'CZ', 'DE', 'DK-E', 'DK-W',
'EE','ES','FI','FR','GR','HR','HU','IE','IT','LT','LU','LV','ME','MK','NI','NL','NO1','NO2','NO3','NO4','NO5','PL','PT','RO','RS','SE1','SE2','SE3','SE4','SI','SK','UK-N','UK-M', 'UK-S']
    genlist = ['Nuclear','Bio-O','Bio-M','Bio-N','Lignite-O','Lignite-M','Lignite-N','HardCoal-O','HardCoal-M','HardCoal-N','Gas Conv-O','Gas Conv-M','Gas Conv-N','Gas CCGT-O','Gas CCGT-M','Gas CCGT-N','Gas OCGT-O','Gas OCGT-M','Gas OCGT-N','GasCCS','Oil-O','Oil-M','Oil-N','Diverse','Other RES','CHP_Coal','CHP_Gas','CHP_Oil','CHP_RES','CHP_Divers']


    try:
        totalUTV = pd.read_csv(r'{}\UTV_hours_AVG.csv'.format(name_dir), header = 0, float_precision='round_trip', encoding ="utf-8", sep=";", low_memory=False)
        total = pd.read_csv('{}\Energymix_Hourly_Average.csv'.format(name_dir), header = 0, float_precision='round_trip', encoding = "utf-8", sep=";", low_memory=False)
    except:
        print("Could not load csv files")
        raise Exception



    nodes = {}
    utv = {}

    #Loading dataframes with RES
    wind_on, wind_off, solar = load_res(name_dir)
    hydro = load_hydro(name_dir)


    for name in namelist:

        tech = pd.DataFrame(np.zeros((8736,30)), columns = genlist)
        imports = pd.DataFrame(np.zeros((8736, 44)), columns = namelist)
        nodes[name] = total.filter(like='%s'%name[:4])              ##Filtering out from Total DataFrame to dictionary with node name as key
        utv[name] = totalUTV.filter(like='%s'%name[:4])

        #Setting header to be generating technology and import node, respectively
        nodes[name].columns = nodes[name].iloc[0]
        utv[name].columns = utv[name].iloc[0]

        #Dropping rows without values
        nodes[name] = nodes[name].drop(index=0).reset_index(drop=True)
        utv[name] = utv[name].drop(utv[name].index[[0,1,2]])
        utv[name] = utv[name].reset_index(drop=True)

        #Updating generating technology names so they coincide with genlist
        nodes[name] = updateTechName(nodes[name])

        #Standardising the dataframes
        tech.update(nodes[name])                            ##Filling in values from nodes[name] into empty dataframe
        #nodes[name] = pd.merge(empty, nodes[name].astype(float), how='right')
```

```
            nodes[name] = tech
            nodes[name] = assignResColumns(nodes[name], name, wind_on, wind_off, solar, hydro)
            nodes[name] = pd.concat([nodes[name], imports], axis = 1)

            #Making entries to float64
            utv[name] = utv[name].astype(float)
            nodes[name] = nodes[name].astype(float)


        print("####Assigning import values to nodes####\n")
        for key in tqdm(utv.keys()):
            print(key)
            for name in list(utv[key]):
                for h in range(0,8736):
                #Setting imports to node and scaling to GWh

                    if (utv[key].loc[h,name] <= 0):
                        nodes[key].loc[h,name] = np.divide(utv[key].loc[h,name],-1000)
                    else:
                        nodes[name].loc[h,key] = np.divide(utv[key].loc[h,name], 1000)




        for key in nodes.keys():
            cols = {x:'Imports_from_%s'%x for x in namelist}
            nodes[key].columns = [cols.get(x,x) for x in nodes[key].columns]
            nodes[key].index = pd.date_range('1/1/2020 00:00', end= '29/12/2020 23:00', freq = 'H').strftime('%d/%m/%Y %H:%M:%S')



        return nodes

def load_res(name_dir):
    print("Loading Wind_on")
    wind_on = pd.read_excel(r'{}\res_reformatted_2040.xlsx'.format(name_dir), index = 0, sheet_name='Wind_on')
    print("Loading Wind_off")
    wind_off = pd.read_excel(r'{}\res_reformatted_2040.xlsx'.format(name_dir), index = 0, sheet_name='Wind_off')
    print("Loading Solar")
    solar = pd.read_excel(r'{}\res_reformatted_2040.xlsx'.format(name_dir), index = 0, sheet_name='Solar')

    wind_on = wind_on.astype(float)
    wind_off = wind_off.astype(float)
    solar = solar.astype(float)

    return wind_on, wind_off, solar

def load_hydro(name_dir):
    hydro  = pd.read_csv(r'{}\EGPR_hours_AVG.csv'.format(name_dir), header=0, float_precision='round_trip', encoding='utf-8', sep=';',
low_memory=False)
    hydro = hydro.astype(float)

    return hydro

def assignResColumns(df, name, wind_on, wind_off, solar, hydro):

    try:
        df['Wind_on'] = wind_on.filter(like='%s'%name[:4])
    except:
        print(name + ' has no onshore wind production')
        df['Wind_on'] = pd.DataFrame(np.zeros(8736))
    try:
        df['Wind_off'] = wind_off.filter(like='%s'%name[:4])
    except ValueError:
        print(name + ' has no offshore wind production')
        df['Wind_off'] = pd.DataFrame(np.zeros(8736))
    try:
        df['Solar'] = solar.filter(like='%s'%name[:4])
    except ValueError:
        print(name + ' has no solar production')
        df['Solar'] = pd.DataFrame(np.zeros(8736))
    try:
        df['Hydro'] = hydro.filter(like='%s'%name[:4])
    except ValueError:
        print(name + ' has no hydro power production')
        df['Hydro'] = pd.DataFrame(np.zeros(8736))
```

```python
    return df



def start_excel_macro():
    #Launch excel and open workbook
    xl = win32com.client.Dispatch("Excel.Application")
    xl.Workbooks.Open(Filename='Data\res.xlsm')

    #Run Macro
    xl.Application.Run("excelsheet.xlsm!modules.module1")

    #Save Document
    xl.Application.Save()
    xl.Application.Quit()

    del xl



def updateUTVName(df):
    columns = df.columns.tolist()
    for i in range(0,len(columns)):
        columns[i] = "Imports_from_%s"%columns[i]

    df = df.columns = columns
    return df

def updateTechName(df):
    tech = ['Bio', 'Lignite', 'HardCoal', 'Gas Conv', 'Gas CCGT', 'Gas OCGT', 'Oil']
    versions = ['O', 'M', 'N']
    cols = []
    count = 0
    for column in df.columns:
        if column in tech:
            cols.append(f'%s-{versions[count]}'%column)
            count+=1
            if(count > 2):
                count = 0
            continue
        cols.append(column)
    df.columns = cols
    return df
```

```python
# -*- coding: utf-8 -*-
"""


@author: OleM

"""

import pandas as pd


def load_emission_factors(name_dir = None):

    if(name_dir is None):
        name_dir = input("Write directory you want to write to: ")

    genlist = ['Nuclear','Bio-O','Bio-M','Bio-N','Lignite-O','Lignite-M','Lignite-N','HardCoal-O','HardCoal-M','HardCoal-N','Gas Conv-O','Gas Conv-M','Gas Conv-N','Gas CCGT-O','Gas CCGT-M','Gas CCGT-N','Gas OCGT-O','Gas OCGT-M','Gas OCGT-N','GasCCS','Oil-O','Oil-M','Oil-N','Diverse','Other RES','CHP_Coal','CHP_Gas','CHP_Oil','CHP_RES','CHP_Divers']
    E_fac_total = pd.read_csv(r'{}\Overview.csv'.format(name_dir), header = 0, float_precision='round_trip', encoding='utf-8', sep=';', low_memory=False)

    efficiency_index = E_fac_total.columns.get_loc('Efficiency %')
    theoretical_index = E_fac_total.columns.get_loc('theoretical CO2 coefficient')
    specific_index = E_fac_total.columns.get_loc('specific CO2 coefficient')
    name_index = E_fac_total.columns.get_loc('Name')

    E_fac_total = updateTechNameRows(E_fac_total, name_index)

    E_fac = {}

    for index, row in E_fac_total.iterrows():
        tech = row[name_index]
        if(E_fac_total.iat[index, name_index] in genlist and not tech in E_fac):
            E_fac[tech] = pd.DataFrame({'Efficiency': E_fac_total.iat[index, efficiency_index], 'Theoretical CO2 Intensity': E_fac_total.iat[index, theoretical_index], 'Specific CO2 intensity': E_fac_total.iat[index, specific_index]}, index = [0])
            E_fac[tech] = E_fac[tech].fillna(value=0.0)

    ##Assigning RES CO2 intensities

    E_fac['Wind_on'] = pd.DataFrame({'Specific CO2 intensity': 0.0}, index = [0])
    E_fac['Wind_off'] = pd.DataFrame({'Specific CO2 intensity': 0.0}, index = [0])
    E_fac['Solar'] = pd.DataFrame({'Specific CO2 intensity': 0.0}, index = [0])
    E_fac['Hydro'] = pd.DataFrame({'Specific CO2 intensity': 0.0}, index = [0])


    return E_fac


def updateTechNameRows(df, name_index):
    tech = ['Bio', 'Lignite', 'HardCoal', 'Gas Conv', 'Gas CCGT', 'Gas OCGT', 'Oil']
    versions = ['O', 'M', 'N']
    count = 0
    for index, row in df.iterrows():
        if row['Name'] in tech:
            df.iat[index, name_index] = f'%s-{versions[count]}'%row['Name']
            count+=1
            if(count > 2):
                count = 0
            continue
    return df
```

```python
# -*- coding: utf-8 -*-
"""

@author: OleM

"""
import pandas as pd
import numpy as np


def load_consumption(name_dir = None):

    if(name_dir is None):
        name_dir = input("Write directory you want to read from: ")

    df_cons = pd.read_csv(r'{}\FAST_hours_AVG.csv'.format(name_dir), header = 0, float_precision='round_trip', encoding='utf-
8', sep=";", low_memory=False)


    df_cons.index = pd.date_range('1/1/2020 00:00', end= '29/12/2020 23:00', freq = 'H').strftime('%d/%m/%Y %H:%M:%S')

    return df_cons
```

```python
# -*- coding: utf-8 -*-
"""

@author: OleM

"""

import pandas as pd
import numpy as np
import os
import pdb
from tqdm import tqdm


HOURS_YEAR = 8736
NR_YEARS = 75

def format_res_excel(name_dir = None, year = 2040):


    pdb.set_trace()
    res = {}
    res['Wind_on'] = pd.DataFrame(index = None, columns = None)
    res['Wind_off'] = pd.DataFrame(index = None, columns = None)
    res['Solar'] = pd.DataFrame(index = None, columns = None)


    #name_dir should be the name of the directory where all VRES files are found
    if (name_dir is None):
        name_dir = input("Write name of directory you read datas from: ")
        #name_dir = check_valid_dir(name_dir, os.getcwd())
        year = 2040


    for filename in tqdm(os.listdir(name_dir)):
        if "OW_W30_Comma" in filename:
            values = pd.read_csv(r'{}/'.format(name_dir) + filename, header = 0, encoding='utf-8', sep='\n', decimal = ',', dtype = np.float64,
low_memory=False)
            node = get_node(filename)
            plant_type = 'Wind_off'

            #Calculate average hourly value given 75 years
            res = calculate_average_hourly_value(values, node, res, plant_type)
            continue

        if "W30_Comma" in filename:
            values = pd.read_csv(r'{}/'.format(name_dir) + filename, header = 0, sep = '\s+', dtype={'GWh': np.float64}, decimal = ",", low_memory=False)
            node = get_node(filename)
            plant_type = 'Wind_on'

            #Calculate average hourly value given 75 years
            res = calculate_average_hourly_value(values, node, res, plant_type)
            continue

        if "S30_Comma" in filename:
            values = pd.read_csv(r'{}/'.format(name_dir) + filename, header = 0, encoding='utf-8', sep='\n', dtype = np.float64, decimal = ',',
low_memory=False)
            node = get_node(filename)
            plant_type = 'Solar'

            #Calculate average hourly value given 75 years
            res = calculate_average_hourly_value(values, node, res, plant_type)
            continue

    with pd.ExcelWriter(r'{}/'.format(name_dir) + 'res_reformatted_'+str(year)+"_float_precision"+".xlsx") as writer:

        res['Wind_on'].to_excel(writer, index = False, sheet_name = "Wind_on")
        res['Wind_off'].to_excel(writer, index = False, sheet_name = "Wind_off")
        res['Solar'].to_excel(writer, index = False, sheet_name = "Solar")

    return res

def calculate_average_hourly_value(values, node, res, plant_type):

    #Much faster running time than by use of nested for loops
    for i in range(HOURS_YEAR):
        temp = values[i::HOURS_YEAR]      #Slices every nth (HOURS_YEAR) row
        tot = temp.mean()             #Average over 75 years
```

```
        res[plant_type].loc[i, node] = tot[0]

    #Slow
# =============================================================================
#     for j in tqdm(range(HOURS_YEAR-1)):
#         sum = 0
#         for i in range(NR_YEARS-1):
#             sum += temp.iloc[i*HOURS_YEAR+j]
# =============================================================================
        #sum = sum/NR_YEARS
        #res[plant_type].loc[j, node] = sum[0]

    return res

def get_node(filename):
    namelist = ['AL', 'AT', 'BA', 'BE', 'BG', 'CH', 'CZ', 'DE', 'DK-E', 'DK-W',
'EE','ES','FI','FR','GR','HR','HU','IE','IT','LT','LU','LV','ME','MK','NI','NL','NO1','NO2','NO3','NO4','NO5','PL','PT','RO','RS','SE1','SE2','SE3','SE4','SI','SK','UK-N','UK-M', 'UK-S']

    for node in namelist:
        if(node in filename):
            return node
    print("Could not find Node in: {}".format(filename))
    return "ErrorNode"
```