Norway´s role as a flexibility provider in a renewable Europe

Short version of a position paper prepared by FME CenSES.

This report is based on a position paper prepared by FME CenSES. For author list, full scientific elaboration and references, we refer to the original paper.

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1 Introduction

The European power system is in transition driven by technological development and political action to combat climate change. The European Commission has made a long-term commitment to reduce carbon emissions by 80-95% by 2050 compared to 2010. Norwegian energy resources can play an important role in this transition.

Even though the renewable sources in Europe will be able to replace large amounts of fossil energy with renewables like wind and solar PV, scenario studies indicate that we will see periods of different durations, from seconds, minutes, hours and up to several weeks, with large amounts of deficit energy and similar periods with large amounts of surplus energy due to the variability in weather. Consumer measures like demand response[1] and demand side management[2] are two of the tools suggested in the Clean Energy for all Europeans package[3] in order to meet this challenge. Still, more capacity for dispatchable energy generation[4] is needed to ensure a stable and reliable power supply.

In a system with high renewable penetration, flexibility is needed to avoid extreme variations in price and potential energy shortages resulting in blackouts when intermittent generation is much lower than the load.

New energy storages, flexible energy sources and flexible energy carriers are vital enablers for increased renewable power production which will contribute to the EU ambition of a low emission energy system. The access to hydropower and natural gas places Norway in a unique position. It is likely that new flexibility and storage services linked to the gas pipeline system and Norwegian hydro reservoirs will be among the more attractive solutions in terms of capacity and cost. Export of flexibility and balancing services can potentially generate high revenue for Norway.

2 What do we mean by flexibility and balancing?

Balancing services are typically services for short-term, automatic balancing in the power network. They can be delivered via flexible producers who can adjust their production levels and by consumers who can adjust consumption in the short term. The total energy content of such services is often low, while the peak energy content and capacity needed may be high. The potential economic value is much higher than the value of the energy content as the services provide stability and security of supply. Such services need high capacity reserved for the services both on the generation side and in cables.

Flexible energy exchange: Exchange of energy is electricity traded between two geographical markets. Value for society is created by importing from markets with lower price and exporting to markets with higher price. The value creation from energy exchange can benefit both

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[1] **Demand response** (DR): changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. (Wikipedia)

[2] **Demand side management** (DSM): initiatives and technologies that encourage consumers to optimise their energy use. (https://www.ema.gov.sg/Demand_Side_Management.aspx)

[3] EC, 2016

[4] **Dispatchable generation** refers to sources of electricity that can be used *on demand* and dispatched at the request of power grid operators, according to market needs. Dispatchable generators can be turned on or off or can adjust their power output according to an order. This is in contrast with non-dispatchable renewable energy sources such as wind power and solar PV power which cannot be controlled by operators. (Wikipedia)

generators, consumers and cable owners depending on market design and regulation. The possibility for energy exchange depends on the degree of flexibility in the system:

Short-term flexibility: when load or generation can be adjusted in time periods ranging from minutes to hours, for example hydropower and demand response. Often this is the same capacity that alternatively can be used to deliver balancing services.

Medium-term flexibility: In systems with high wind penetration there are often periods of several weeks with low generation from the intermittent resources. This requires access to alternative generation capacity with flexibility to generate for several weeks and to store energy, for example hydropower plants with reservoirs or natural gas power plants.

Seasonal flexibility: Hydropower systems with reservoirs, natural gas in reservoirs and some thermal heat storage systems can store energy between seasons to smooth out seasonal differences in price, creating value in similar ways as exchange between different price regions.

3 Scope

The purpose of this report is to study how and at which capacity Norwegian resources can provide flexibility for Europe in a cost minimizing integrated European energy system. It summarises our knowledge on the following issues:

- How will different policy and technology scenarios influence Europe’s need for balancing and flexibility at different time horizons?
- How can Norwegian capabilities be part of the solution by providing flexibility to the European energy market from the hydropower and the natural gas system?
- Which uncertainties are potential investors in energy infrastructure and generation capacity providing flexibility to Europe faced with?
- How may these uncertainties be reduced and by whom?

We present different alternative developments for the European energy system and discuss the need for Norwegian flexibility in these scenarios.

We only study the power market. This means that natural gas power plants represent the only intersection between the natural gas system and the power system.

We also allow the model used in the studies to invest in Norwegian wind resources, leading to a situation where Norway is a net exporter of energy.

This report contains several elements that are still work in progress, and new results will follow as we get a better understanding of European climate policy and the role of renewables.

Changes in Norwegian energy demand, for example increased national use, which would be an alternative to the net export suggested by the model studies and could potentially increase the value of Norwegian resources further, are not included in this study.

4 The Norwegian power and natural gas system – status and expected developments

4.1 The Norwegian power system

Electricity production in Norway has been based on hydropower from the very start more than a century ago. This explains the high share[5] of renewable energy in Norway's total energy consumption.

Hydropower production varies during the year and from year to year, depending on inflow and on demand for electricity.
Almost 1600 hydropower plants are in operation throughout Norway, with a total capacity of 31 837 MW with additional 2200 MW in construction and an additional 5500 MW approved[6]. 80% of these plants are small, with a capacity of less than 10 MW each. The potential is still large with many projects on the drawing board, in the application phase or waiting for grid development.

An important characteristic of the Norwegian hydropower system is the large energy storage capacity, which amounts to approximately 85 TWh. This is nearly half of all hydroelectric storage capacity in Europe[7].

There are three reasons for this:

1. a large seasonal variation of inflow
2. no thermal backup in the system
3. low cost for reservoirs due to favourable natural conditions.

Most of the hydropower system and nearly all the storage was constructed before 1995. In later years, mainly small hydropower without storage has been put in operation.
The large storage capacity was mainly designed for seasonal storage of water. In Norway, the largest inflow usually occurs during spring and summer when electrical energy consumption is at its lowest. In winter, the inflow is very low, while the electrical energy consumption is at its highest. The reservoir capacity will usually be large enough to store all the energy needed during the next winter, except in uncommonly dry years. The seasonal variation shows a maximum in late summer and a minimum at the end of the winter, but reservoirs nearly always have some free capacity.

Norway and Sweden agreed on a joint el-certificate scheme ("Green-certificates") in 2012 to promote development of more renewable energy to meet the RES-Directive target for 2020. Most of it is estimated to be implemented as hydro in Norway and wind and bio-energy in Sweden[8].

Transport and distribution of electricity is done in the electricity grid, the connection between generation facilities - mostly large hydropower plants - and the end users. The main grid in Norway (11 000 km in total) consists of overhead lines (99%), underground cables, and some submarine cables. This grid is mainly (96%) owned and operated by the transmission system operator Statnett and a few other large grid companies.

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[5] 69% in 2014 (Statistics Norway, 2016)

[6] https://www.nve.no/energiforsyning-og-konsesjon/vannkraft/vannkraftpotensialet

[7] Pumpekraft i Norge. Kostnader og utsikter til potensial. *Norwegian Water Resources and Energy Directorate*: Rapport 2011/22. Oslo.

[8] OED 2012

The major power flow in Norway is from the large generation facilities in the west to the main demand centres in the east. However, with an increasing number of international links, there will be a gradual change to a north-south flow. Norway is currently connected internationally by overhead power lines to Sweden, Finland and Russia and by submarine HVDC[9] cables to Denmark and the Netherlands.[10] Two new submarine cable connections are under construction, one from Tonstad to Schleswig-Holstein in Germany and one from Kvilldal to Blythe in England[11]. By 2020, the total transmission capacity from Norway to other countries will be around 9200 MW, of which 5200 MW submarine cables and 4000 MW overhead power lines.

Investments in the high voltage power system infrastructure are expected to reach a total value of 35-45 billion NOK[12].

The profitability of a hydro storage facility depends on the price differences between day and night and, with larger storage capacity, during the week. For Norway, the storage capacity depends on the size and flexibility of reservoirs and the ability to hold back production in hydro plants. Norway utilises the ability to import during the night when prices are low, such that hydropower can be exported during the day when prices are higher. Generation capacity during the day and cable capacity are the limitations for this strategy as well as its dependence on price variations in the European markets.

To increase the generation capacity further, pumped storage power plants can be used, where the imported electricity is used to increase the water level in the reservoirs and thus also the export potential when prices are favourable. The attractiveness of both solutions decreases when European electricity prices vary less and increases when they vary more.

Currently, it is very difficult to find profitability for pumped storage power plants in Scandinavia since power price variations during the day are rather small due to the high flexibility of the hydropower system. However, more renewables and a stronger interconnection of the Norwegian and the German system could trigger profitable conditions for pump storage and the possibility to provide the extra flexibility. In the future, these patterns may change as solar PV is expected to take a central role in the European power mix.

4.2 The Norwegian natural gas system

Natural gas represents more than 20% of the energy demand worldwide, and Norway is the third largest gas exporter in the world[13]. Norwegian gas covers approximately 25% of the EU gas consumption and, measured by energy content, its production is about 10 times the size of the Norwegian power production. The expected pipeline gas export in the years from 2020 is around 120 billion standard cubic metres (GSm^3). In 2017, the Norwegian export of natural gas was approximately 122 GSm^3 of which 117 GSm^3 were delivered to terminals in Europe.

From 2020 on, production levels depend on unknown resources, which have a substantial higher uncertainty when it comes to total volume, localisation, timing, and size of each discovery.

Natural gas is efficient to transport and easy to store. It can be stored

1. by varying the production rates in the fields, using the reservoirs as storages

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[9] HVDC: High-voltage, direct current (høyspent likestrømsoverføring)

[10] Sweden between 3700 and 4000 MW, Finland 50 MW, Russia 50 MW, Denmark 1700 MW and the Netherlands 700 MW.

[11] Each with a capacity of 1400 MW

[12] Statnett, *Nettutviklingsplan 2017*.

[13] https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/

2. in conventional natural gas storages
3. as liquefied natural gas (LNG)
4. in the transportation system itself.

Approximately 95% of the natural gas from the NCS is exported through the pipeline network to terminals in Germany, Belgium, France and the UK. This export system consists of nearly 8000 km of high-pressure subsea pipelines and three processing plants. In addition, the LNG terminal at Melkøya produces LNG of gas.

Traditionally, Norwegian natural gas has been sold through long-term contracts. These are still dominant, but also short-term markets have emerged after the liberalisation of the European markets. The liberalisation process has led to an unbundling of the ownership structure in the natural gas value chain and ensured third party access to the transportation system.

Flexibility

The gas network can be used to achieve flexible deliveries to the markets through:

1. the gas pipeline inventory
2. substantial capacity for varying production in flexible gas fields
3. conventional gas storages

4.2.1 The gas pipeline inventory

The interactions within the value chain are complicated, and the links to quality of service and security of supply are very important. But the total capacity and the ability to adjust inventory in the system appear to be substantial.

The Norwegian natural gas pipelines are highly utilised and will continue to be so during the coming decade, providing a cost-efficient energy supply network to Europe. The shippers have flexibility with respect to booking levels and timing. In addition to long-term booking, it is possible to book capacity on a day-to-day and within-day basis. There are also instruments for re-allocating unused capacity to new shippers. The storage capacity in the transportation system is due to the considerable inventory of natural gas in the pipelines. Currently, this flexibility is primarily used to maintain a high level of security of supply in the system, and to maximise the flow rate in the network.

Some of the inventory in the pipelines is offered to shippers to handle events in the network, such as maintenance. The remaining margin between theoretical capacity and available capacity is due to a safety margin for handling uncertainties (such as sea temperature that will influence the flow rate) and transient flow.

Currently, there is no commercial service that offers booking of inventory in the pipelines to shippers. Utilisation of the storage capacity in the pipelines may offer additional value in the future, provided a market for such services is developed. This could allow shippers to use the pipeline inventory in the large export pipelines to offer flexible services to the European market. Volumes of natural gas could then be reserved and delivered when necessary, analogous to balancing services in the power sector.

With the current operational pattern where the network is run to the capacity limit in winter time, there is limited capacity available for such services. If the flows are further from the capacity limit, however, this capacity might be substantial in terms of energy content. When considering energy scenarios towards 2050, where the European demand for natural gas will increase in volatility and the demand patterns change due to a higher share of renewable production, this storage potential may become very valuable. The costs of operating the network will increase if the pipeline inventories are increased. These costs must be covered by the premium given to the gas delivered as a flexible energy service.

4.2.2 Flexible gas fields

Fields with a lot of flexibility in natural gas production are called swing producers. The amount of flexible production capacity depends on the relation to oil production in the same field. Due to the superior oil price relative to the gas price, oil production is given priority. The operational flexibility for the natural gas production is therefore limited in fields where the gas is associated to oil. There are however also fields on the Norwegian Continental Shelf (NCS) with a high swing ratio, such as Troll and Ormen Lange.

5 The need for flexibility, balancing services and storage due to increased renewable energy production

5.1 Integration of renewable energy into the grid

The ease of integration of renewable electricity technologies into the power grid will depend on three main parameters:

1. dispatchability
2. predictability
3. capacity

Technologies with high dispatchability have some storage, like bio-energy and geothermal, whereas reservoir hydro has large storing capacity. These technologies can adjust their output to a varying demand and will therefore have a high value for supporting the grid under variable load and supply conditions. The main difference between these three dispatchable renewable energy technologies is that hydro can respond within seconds to minutes, whereas the changes in output for bio-energy and geothermal can take up to hours.

Technologies with low dispatchability like solar PV, wind and ocean energy have no storage component and power must be produced instantly following the resource (sun, wind, waves) and its variability. These are also more difficult to predict and therefore more difficult to integrate, especially as their share increases.

Small hydro[14] and run-of-river hydro fall somewhat in between. They are better than wind and solar PV in that respect, but not as good as reservoir hydro or bio and geothermal energy.
Pumped storage hydro (PSH) is a special case of reservoir hydro, normally only used for balancing and energy storage in many electricity systems.

5.2 Sources of variability in generation

Renewable electricity production is generated from natural sources, all of which have characteristic variations with time scales from minutes to years. The three most important renewable energy sources, hydro, wind and solar PV, have very different patterns of variability, but when combined, they can give a more seasonally even distribution.

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[14] **Small hydro** is the development of hydroelectric power on a scale suitable for local community and industry, or to contribute to distributed generation in a regional electricity grid. The definition of a small hydro project varies, but a generating capacity of 1 to 20 MW is common. (Wikipedia)

To maintain a stable frequency in the grid, the total generation and total consumption must balance. If a deviation occurs, counter-measures need to be taken to bring back the balance. ”Balancing power” is power production that can be stepped up or down quickly to counteract the imbalance and to support stability in the grid.

5.2.1 Seasonal variability

Wind power in the North Sea and energy inflow in the Norwegian hydropower system have very different seasonal profiles, but combined they can give a better match to demand.

5.2.2 Variability at intermediate timescales

In wind power, for example, there can be very large and rapid variations in total generation with ramping-up or -down of several thousand MW in the course of a few hours.

A potential future North-Sea wind power system, comprising numerous offshore wind farms, can have a total installed capacity of about 90GW. In this system there can be week-long high and low generation events with positive or negative deviation larger than 30GW compared to average generation. To balance out such events it is necessary to store very large volumes of electrical energy, up to 5TWh for several weeks, and then return this to the grid during the next low event[15]. This amount of energy cannot be stored in ordinary pumped-storage reservoirs only.

5.2.3 Short term variability

Even though wind power generation mainly fluctuates between high and low production following weather patterns at a weekly scale, it may also change within hours from almost full load to almost no load (e.g. storm fronts resulting in a shutdown of wind turbines). This is challenging for the energy system to handle and requires short-term balancing capacity.

In solar PV, short-term variability is mostly due to the deterministic diurnal signal in solar input. Generation can vary extremely fast in just a few hours, with an extremely high maximum ramping-up and -down speed.

The deterministic diurnal cycle in solar radiation is modified by atmospheric conditions, first of all by clouds. Even if some radiation still reaches ground in cloudy weather, the power generation will be strongly reduced. This creates elements of low predictability in generation and increases the need for balancing power from other sources.

5.3 Energy Storage

There will always be a mismatch between energy demand and energy supply. Therefore, storage is needed in all energy systems to ensure a secure supply. With growing penetration of non-dispatchable renewable energy generation, the need for storage will increase.

Energy storage provides essential services along the whole energy value chain:

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[15] Tande, J. O. G., Korpås, M., Warland, L., Uhlen, K., & Van Hulle, F. (2008, May). Impact of TradeWind offshore wind power capacity scenarios on power flows in the European HV network. In Proc. 7th Int. Wind Integration Workshop.

- Balancing demand and supply at many temporal scales
- Managing transmission and distribution grids to ensure the quality of electricity delivered and optimising the need for grid
- Security of supply to ensure back-up source for energy and electricity production

Due to its cross-sector nature, energy storage will also affect well-established markets such as the gas market (e.g. power-to-gas[16]), local heat markets (e.g. heat storage), and the transportation market (e.g. electric mobility, fuel cells).

All energy storage methods and technologies have different properties and wide range and high variation in use, costs, power, energy and applicability. Pumped storage hydro (PSH) has by far the lowest capital cost per unit and is therefore the most applied storage technology to date.

As the Norwegian electricity system is dominated by storage hydro, hydropower is the only technology used for energy storage and balancing the system at time scales from seconds to years. Norway has large hydro reservoirs with large generation capacity and may also store water between years, with no need for extra pumped hydro storage for domestic use. The few existing pumped hydro installations in Norway are mainly used for seasonal pumping and storage.

The cost of line pack in gas pipes as storage will mainly be the additional cost of compressing the natural gas for storage purposes. This may be around 1-2% of the gas. The relevant time horizon for storage services from line pack would be from hours up to days. The volumes will be time dependent but in the order of more than 100 GWh for large export pipelines in a 12-hour horizon.

Based on the presentation in this section, we argue that there is an evident need for balancing services and flexible energy supply in energy mixes that contain a large share of non-dispatchable energy sources. The status of current storage technology (and costs) also indicates that the hydropower reservoirs and natural gas storages can play an important part in offering such balancing services. The pumped storages can then also be used to further increase the storage capacity in the hydropower system.

6 Scenario studies of the European energy system

In order to assess the role of Norwegian hydropower and natural gas in a low-carbon European power system, we applied the investment model EMPIRE[17] in which we constructed a baseline decarbonisation scenario. As one of the key uncertainties in the future development of the European power system is the availability of carbon capture and storage (CCS) for power generation, the Baseline scenario, in which we assume that CCS technologies are implemented commercially, was contrasted against a scenario where CCS is not available (the no-CCS scenario).

The objective is to minimize system cost of the European power system including investment cost and expected operational costs[18]. The model represents load and RES generation under short-term uncertainty, so that hourly variations and their correlations are considered when designing the system. EMPIRE can model the interplay between low-carbon technologies with

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[16] **Power-to-gas** (**P2G**) is a technology that converts electrical power to a gas fuel (…) using electricity to split water into hydrogen and oxygen by means of electrolysis.

[17] EMPIRE is a multi-horizon stochastic capacity expansion model for the European power system., developed in CenSES.

[18] Skar et al, 2016

different characteristics such as solar PV, wind energy, CCS and nuclear power. Flexibility options such as demand response, energy storage and grid expansion are also included.

6.1 EMPIRE Baseline decarbonisation scenario

The baseline scenario comprises a set of assumptions regarding parameters used in the system optimisation in EMPIRE. Some of the most important drivers for the need of investments in a power system are development of demand for electricity and fuel prices.

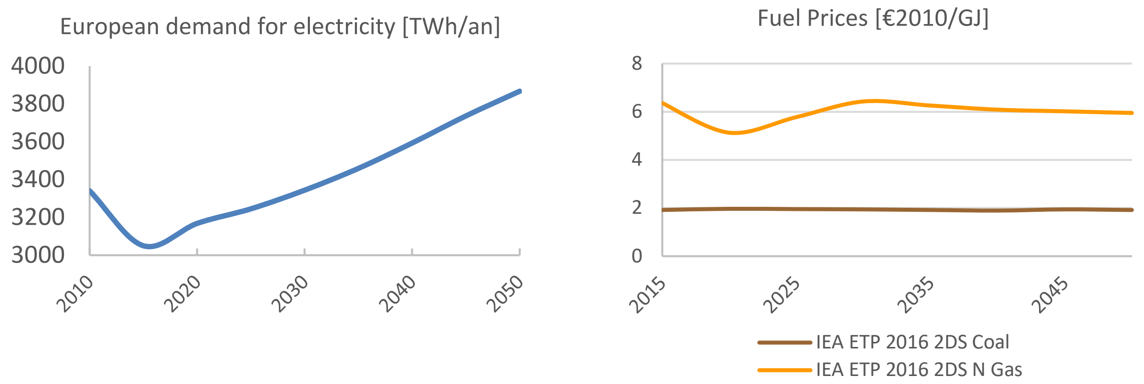

Figure 1 Assumptions about demand for electricity and fuel prices in the baseline scenario

6.1.1 Optimal development of the European power system computed by EMPIRE

In this section we present the EMPIRE results from our Baseline and NoCCS scenarios with a focus on the Europe-wide implication of decarbonisation of electric power.

6.1.1.1 Baseline results

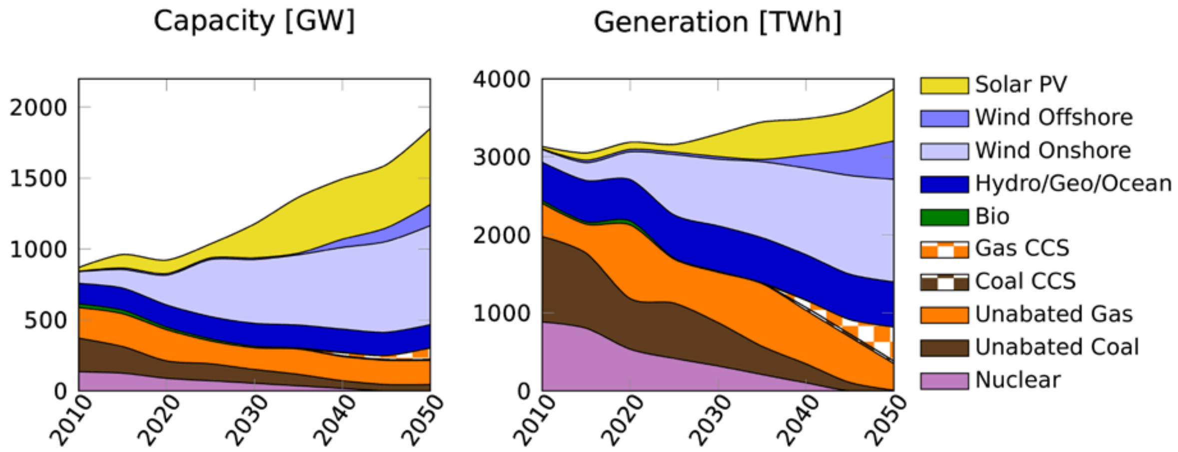

Figure 2 Generation capacity and energy mix in Europe in the Baseline scenario (from EMPIRE)

In 2010 and 2015 most of the generated power came from coal, nuclear, hydropower and natural gas. As the emission limit is progressively decreased, power production from coal is displaced by power produced by natural gas, wind and solar. Nuclear power is steadily phased out from 2015. In 2020, there is a sudden increase in natural gas generation, which is an effect of the low gas price for this period. Wind energy quickly becomes the technology with the highest share of the energy mix in 2025 and onwards. Offshore wind only enters significantly from 2040. In 2050, almost 50% of the total power generation comes from onshore and offshore wind. After 2030, decrease in PV investment costs will have made the technology so competitive that a surge of new capacity enters the market.

In the period from 2018 to 2030, natural gas continues to have a significant share of the generation mix. In 2040, fossil generation with CCS begins to enter the system, while unabated natural gas power production remains at the same level, leading to an overall increase in natural gas power generation. Although a small part of CCS is used for coal, the total CCS portfolio is almost exclusively gas-fired power plants.

Although renewable technologies and batteries see remarkable drops in costs over the course of our analysis period, there is still a fair amount of natural gas production left in the system. The short-term variations in generation from wind and solar PV, combined with variations in load, require flexibility. The competitiveness of these technologies is overestimated. Even with formidable cost decreases for e.g. solar PV, other technologies are also significantly present in the cost-optimal energy mix.

The total increase in capacity and generation from hydropower in Europe is negligible compared to the other technologies.

By 2050, CCS power generation accounts for 12% of the total mix, while the share of wind power is 47%, including both onshore and offshore. By then, most of the conventional (unabated) coal generation will have been retired. Some conventional natural gas generation is still operational, but the total production is low, which means that these power plants are idle for large parts of the year.

By 2050, the net energy balance for Norway is expected to be 112 TWh/y and the total demand is assumed to be about 150 TWh/y.

The optimal strategy found by EMPIRE tends towards deploying new wind generation massively in favourable locations.

6.1.1.2 No-CCS results

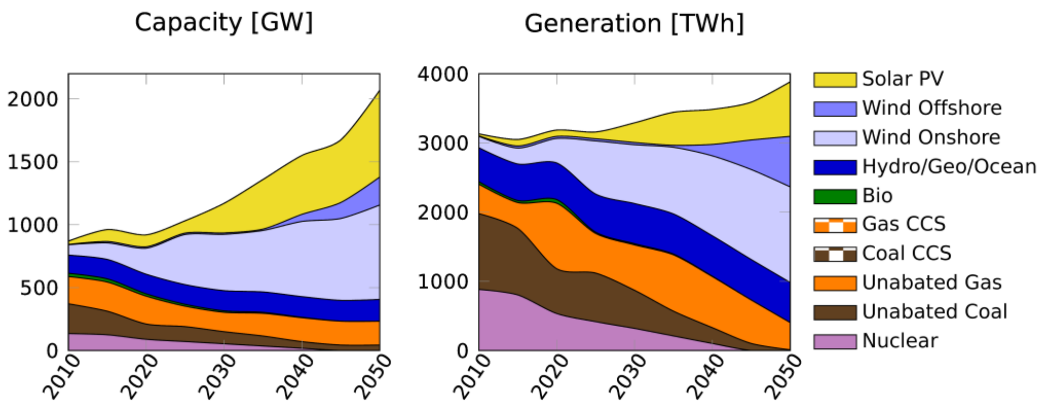

Figure 3: Generation capacity and energy mix in Europe in the NoCCS scenario (from EMPIRE)

The NoCCS scenario closely resembles the Baseline scenario until 2040. After that, when CCS capacity enters in the Baseline scenario, there are notable differences and some similarities. Conventional coal and nuclear power are still phased out. Conventional natural gas power production is slightly higher than in the Baseline scenario. Naturally, all the renewable generation technologies have higher installed capacities in 2050, with a total addition of almost 300 GW.

The European capacity and generation results for the NoCCS scenario in 2050 show that wind (onshore/offshore) and solar PV have a total share of the generation mix of 75% (compared to

65% in the Baseline scenario). There is still a significant amount of natural gas power production in 2050 with a total of about 400 TWh/y, close to the level of 2010.

6.1.1.3 Transmission system expansion

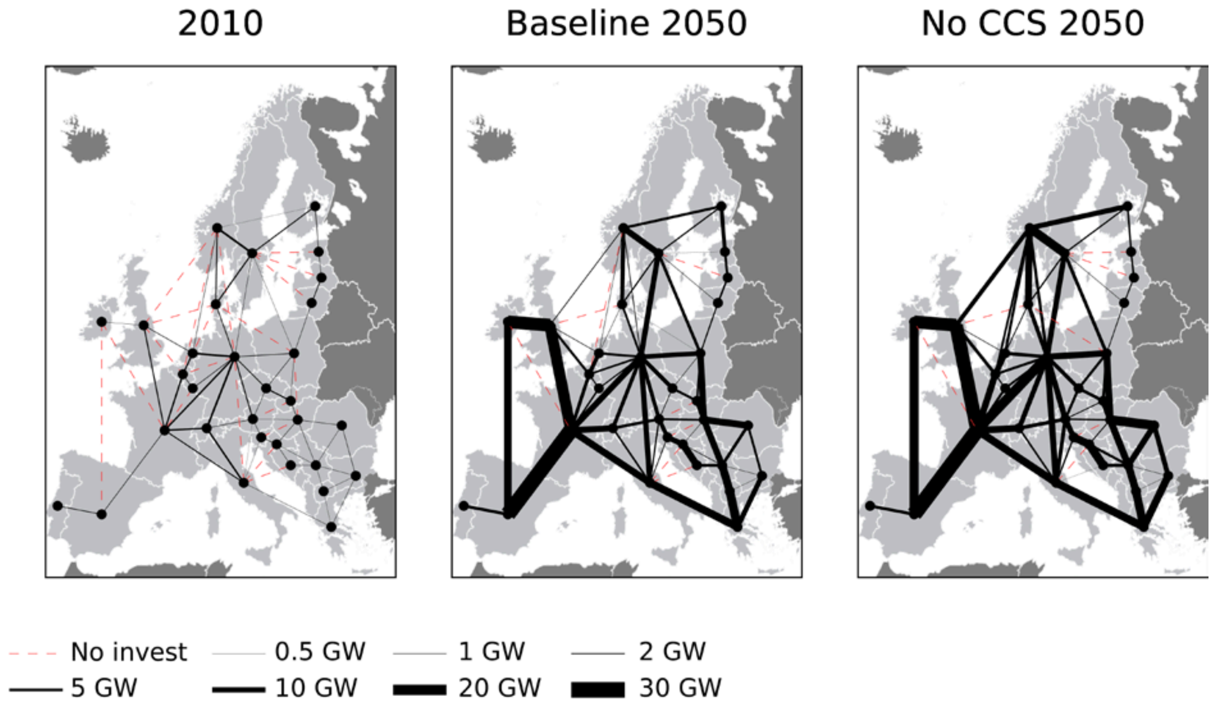

Figure 4: European transmission capacity in 2010, and the EMPIRE optimised infrastructure in 2050 for the Baseline and NoCCS scenarios

Figure 4 shows the initial transmission capacity in the European system as of 2010 and the system as of 2050 from the EMPIRE optimisation, both for the Baseline and for the NoCCS scenario.

In both decarbonisation scenarios there are substantial investments in interconnector capacities. Across all interconnectors the total capacity in Europe was about 65 GW in 2010. By 2020, this is almost doubled, to 120 GW. By 2050 the total capacity in the system (across all interconnectors) is 456 GW in the Baseline scenario, and 527 GW in the NoCCS scenario, a 701% and 811% increase, respectively, from 2010.

These numbers reflect that an optimal decarbonisation relying on large shares of intermittent renewables requires significant transmission system expansion. The need for such infrastructure investments is lower when CCS is available.

In terms of connections between Norway and the rest of Europe there is a significant difference between our two scenarios. In the Baseline scenario, none of the long-distance cables to Germany, Great Britain and the Netherlands are expanded beyond the 2020 capacities. The interconnectors to Denmark, Finland and Sweden are reinforced, and the total exchange capacity is tripled from 2020 to 2050.

6.1.2 The role of natural gas in a low-carbon European power system

Natural gas plays a significant role in the current fossil fuel mix of European power generation. The total natural gas power production in the EU in 2017 was 21% of the total generation mix, and 50% of the total fossil fuel share[19]. In both our decarbonisation scenarios natural gas power production is seen to dramatically increase in 2020 due to low fuel prices. Beyond 2020, natural gas production is reduced from the record high level but remains at a higher level than today until 2040. Then, the total production remains almost the same in the Baseline scenario whereas in the NoCCS scenario it is reduced by almost 50%.

Our analysis shows that without CCS, the natural gas generation needs to be further reduced to achieve the targeted emission reductions.

7 The role of Norwegian energy resources for balancing and flexibility

7.1 Norway's role in a decarbonised European power system in 2050

In both our decarbonisation scenarios there are significant structural changes to the European electric power supply in the period 2010 to 2050. The differences between both scenarios become more and more noticeable towards 2050.

When we isolate Norway, we see that, although there are changes to the electricity supply and a difference in the resulting system in 2050 between the Baseline and NoCCS scenarios, there are also similarities.

The biggest difference between the scenarios with respect to Norway is the additional offshore wind power production which is deployed in the NoCCS scenario. The production from offshore wind adds to the Norwegian power surplus which is already significant in the Baseline scenario. As a result, almost all this new generation is exported to neighbouring countries.

The seasonal exchange is dominated by export all year round, with high export in winter time and reduced export during spring and summer. This is an effect of hydro-production almost balancing demand in these seasons, while at the same time the wind production is high. Export patterns from Norway with this type of technology mix will be highly affected by the wind power production patterns. This is particularly true for the NoCCS scenario where Norway is exporting twice its own consumption, which is mainly offshore wind production.

From a Norwegian perspective it is interesting to observe that the expansion includes heavy investment in capacity towards Sweden and further on to the rest of Europe. This is due to the model minimizing the system wide cost, without considering country specific interests. Depending on market design and tariffs, direct cables may make more sense from an isolated Norwegian value creation perspective. This points to a central challenge in the transition of the European power system: how to share the benefits, costs and risk in the expansion.

In the NoCCS scenario there are huge expansions of all interconnectors. The 2050 total interconnector capacity is increased sevenfold from 2020 in the NoCCS scenario. The large difference in interconnector capacity between the Baseline and NoCCS scenarios can easily be explained by the additional offshore wind investments in Norway in the NoCCS scenario. The additional interconnector capacity is used to export this surplus to continental Europe.

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[19] ENTSO-E's "Statistical Factsheet 2017"

7.1.1 Hourly utilisation of Norwegian resources and exchange with Europe

There are clear trends in the exchange patterns between Norway and its neighbouring countries. In winter time, Norway is a net exporter for most of the time in a typical week, but the full potential export capability is only used for a small share of the time.

In the summer season, representative week profiles show distinctive features. The flexibility of the Norwegian system adapts to the European solar PV production. Although solar PV only comprises 17% of the generation mix, it has a strong impact on the operation of flexible generation resources due to the single sharp diurnal peak in solar generation.

There is a clear positive correlation between hydropower production profiles and the exchange. High export periods coincide with periods of high production from hydropower, and low export (and import) coincide with low hydropower production. This is a strong indication that the hydropower production pattern is driven by the operation of the European generation portfolio (to a large extent wind and solar), and not by Norwegian load.

In the NoCCS scenario, the exchange and hydropower production profiles look strikingly similar to the Baseline results, albeit with much higher absolute variation and peaks in the exchange. This is as expected due to the increased exchange capacity in the NoCCS scenario compared to Baseline.

7.2 Within-day flexibility in the natural gas network

As with hydropower, natural gas power generation can be a flexible resource in a low-carbon power system.

High mid-day solar production forces flexible natural gas power plants in European countries connected to Norway through natural gas pipelines to shut down for several hours a day, causing steep ramps. Frequently, the natural gas portfolio of these countries ramps a full cycle from full production to almost no production and back to full production in the course of one day.

Comparing the Baseline and NoCCS scenarios shows that natural gas with CCS is typically utilised as baseload generation. The most significant (rapid) changes in generation from natural gas are found at the unabated power plants.

In both scenarios it is evident that

1. unabated natural gas power plants (for the most part CCGTs[20]) must be designed and configured for a highly flexible operation with steep ramps, heavy cycling and potentially frequent start-ups and shutdowns.
2. the natural gas fuel supply to these plants must be able to handle these large variations in production, otherwise local fuel storage needs to be considered.

7.3 Balancing in the short-term (seconds to minutes) providing system services and regulation services using flexible hydropower

7.3.1 Integration of Regulating Power Markets in Northern Europe

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[20] CCGT: Combined Cycle Gas Turbines: energy generation technology which combines a gas-fired turbine with exhaust heat recovery which is then used by a steam turbine.

There are potential operational benefits and challenges of exchanging balancing services between the Nordic countries and continental European countries for regulation and reserve purposes in the short time horizons from seconds to minutes.

The SINTEF Energy Research project "Balance Management in Multinational Power Markets[21] highlights the potential of Nordic hydropower production flexibility, the benefits of cross-border cooperation and the necessary transmission capacity in order to reduce the challenges related to variability and uncertainty of power generation from renewable energy sources in Northern Europe.

Case studies of a 2010 and a 2020 scenario[22] show that there are considerable changes in the operation of the power system between 2010 and 2020. With a significant increase in interconnection capacity, the exchange between the Nordic system and continental Europe is nearly doubled. The impact of variable inflow to the Nordic hydropower system is reduced, but due to the wind power production a higher short-term volatility of the system dispatch and consequently of electricity prices is observed.

Results also indicate higher system imbalances and hence costs in the balancing power market. An integration of national balancing markets in Northern Europe provides a good possibility to counteract this cost increase, while the system security is enhanced at the same time.

The case study for the integration of Northern European balancing markets shows significant economic benefits. When exchange of reserve capacity is made possible, in average 20% of the reserve capacity required in the continental area will be procured in the Nordic countries. This results in annual savings of about EUR 40 million. Furthermore, the activation of balancing reserves can be reduced by 40% due to system-wide netting of imbalances[23], resulting in additional savings of at least EUR 100 million.

7.3.2 System Impacts from Large Scale Wind Power

Aigner[24] evaluated further system impacts of large-scale wind power and proposed measures for a cost efficient and secure integration in the power system. The focus was on the development of a high-resolution wind power production model, a joint grid expansion model and the development of market models to simulate an integrated intra-day and balancing market in Northern Europe to illustrate the role of Nordic hydropower to even out the wind power variations in the continental system.

Even though offshore wind installations only correspond to about 20% to 25% of the total installed wind generation capacity in Europe, they are responsible for 40% to 60% of the overall hourly fluctuations. [25]

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[21] http://www.sintef.no/Projectweb/Balance-Management/ initiated in 2007 in order to in order to study the cross-border exchange of balancing services between different countries and the development of multinational balancing markets.

[22] Jaehnert, 2012, investigating the large-scale wind integration in the power system using two interacting models, a short-term balancing market model and a spot-market model, EMPS

[23] The term "netting of imbalances" is used to describe a balancing market design where the resulting deviation is calculated as the net deviation in several control areas (countries). If one area has a negative deviation while another has a positive deviation the net effect is zero and there is no need to perform control actions.

[24] Aigner, T. (2013). System impacts from large scale wind power., PhD thesis, NTNU

[25] Aigner, T., & Gjengedal, T. (2011, August). Modelling wind power production based on numerical prediction models and wind speed measurements. In *17th Power Systems Computation Conference, Stockholm*.

Although the hourly wind power production variability will increase significantly, its effect on the European net load[26] variability remains limited. While in 2020 almost no increase in net load variations can be detected on a European level, the variability will only increase by about 3 GW/h in 2030.

Gross system imbalances and gross balancing energy are almost doubled in the 2020 scenario compared with the 2010 scenario without balancing market integration. With an overall amount of EUR 343 million the reserve procurement costs are more than twice as high as the 2010 results. The system balancing costs are estimated to EUR 154 million in 2020 increasing by about 25% in comparison with the costs in 2010.

Using the possibilities of a fully integrated market with its system-wide reserve procurement and exchange possibilities, the 2010 procurement costs can be cut down by 40% while in the 2020 scenarios the costs are reduced by about 30%. Almost the same conclusion can be drawn for the balancing costs, being reduced by 30% and 50% in the 2010 scenario and the 2020 scenario respectively by utilising the flexibility of the Nordic hydropower. As most of the cheap balancing resources are situated in the Nordic area, the exchange of balancing reserves will increase and become more and more important in future scenarios, while the activation of reserves in continental Europe will decrease.

7.3.3 Integrated Power System Balancing in Northern Europe

A study by Farahmand[27] includes a two-step model for the optimal procurement of reserve capacity and activation of balancing services within a framework of a joint market for energy and reserve capacity, which leads to better utilisation of the interconnections by avoiding socio-economic losses in the day-ahead market imposed by a fixed reservation of the corridors for reserve exchange.

Quantifying the potential benefits, i.e. socio-economic cost reduction, for the simulated year of 2010 indicates that through the integration of balancing markets in the northern European area, there is a potential of EUR 400 million operational cost savings per year.

For 2030, the expected large-scale integration of wind power into the northern European power system brings along significant challenges for system planning and operation. The annual expected operational cost saving is EUR 512 million, which is 30% of the system balancing cost. Norway provides the main share of upward balancing reserves exported from the Nordic to the Central European system; almost 76% of the total exported values. Also, it turns out that activated reserve is reduced with 24% due to the effect of imbalance netting.

7.3.4 Balancing market design with a sequential market clearing

A further study refers to the modelling of an integrated balancing market in a setting similar to the current sequential market clearance order in Europe[28]. The sequential setup is used to analyse the impact of balancing market integration in the current European electricity market settings and allows the comparison of different market designs.

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[26] Net load describes the remaining demand for dispatchable power plants, i.e. demand minus production from intermittent renewable energy sources

[27] Farahmand, H. (2012). Integrated power system balancing in northern europe-models and case studies., PhD thesis, NTNU

[28] Gebrekiros, Y (2015)., Analysis of Integrated Balancing Markets in Northern Europe under Different Market Designs, PhD thesis, NTNU.

The conclusion is that collaboration on system services for short horizons is beneficial. The possibility of cross-border balancing energy exchange gives cost reduction benefits in comparison to local balancing. The decrease in balancing costs is due to the netting of imbalances and the use of cheaper balancing energy from neighbouring zones. Due to the general improvement in market efficiency, the integrated flow-based balancing energy market clearing results in 20% lower balancing cost compared to the NTC based approach.

7.4 Use of Norwegian hydropower to provide medium-term flexibility and energy storage

As shown by the EMPIRE analysis, there is a potential for using Norwegian hydro to provide balancing from between hours up to days. When it comes to the longer time periods of balancing demand and supply when intermittent generation is low for weeks, there are very few alternatives to hydropower with large reservoirs if CO_2-emissions should be avoided.

This is confirmed by a CEDREN study[29] which investigates the potential contribution from Norwegian hydropower to the European energy system.
Many European countries have few natural lakes and no available existing reservoirs for pumped hydro storage. Norway has large reservoirs and/or lakes used for traditional hydropower production, and it may be possible to increase the capacity by using existing reservoirs. The case-study from CEDREN investigates development of storage hydropower and pumped storage in Norway with storage volumes that could serve balancing and storage needs for several weeks.

The study concludes that it is feasible to install about 20 000 MW in new capacity in Norwegian hydropower without large environmental impacts because water level fluctuations would be moderate even though more than 5 TWh storage capacity may be used at any time.[30]

8 Flexibility from the Norwegian energy system

8.1 Opportunities

With a massive expansion of Norwegian renewable generation without a similar increase in load, as described in the two EMPIRE scenarios (with CCS and NoCCS), Norway will be a net exporter of energy. An added value from this export comes from flexibility which creates opportunities for the future Norwegian energy system in its interaction with the rest of Europe.

Short-term flexibility: Both EMPIRE scenarios show active use of the flexibility in the Norwegian hydropower system. *The hydropower system makes it possible to optimise the daily export and import profile in order to export more when the prices are high and export less or import when prices are low. The flexible hydropower is also important to increase the value of other renewable resources in Norway because the net export can be managed flexibly.*

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[29] Harby, A., Sauterleute, J., Korpås, M., Killingtveit, Å., Solvang, E. and Nielsen, T. (2013). "Pumped Hydro Storage". *In* Stolten, D. & Sherer, V. (eds) 2013. Transition to Renewable Energy Systems, Wiley-VCH.

[30] For more information on these studies and the use of pumped hydropower, see Graabak, I., Jaehnert, S., Korpås, M., & Mo, B. (2017). Norway as a Battery for the Future European Power System—Impacts on the Hydropower System. Energies, 10(12), 2054.

Medium-term flexibility: *Our studies show that the flexibility of hydropower is unrivalled when it comes to providing this type of flexibility when CCS is not a commercial technology. If CCS is a commercial technology, natural gas with CCS can provide such flexibility as well due to the flexibility in natural gas pipelines.*

Seasonal flexibility: *The EMPIRE analysis shows that there are clear seasonal differences in the export/import patterns in cables and in the power generation (both hydropower and natural gas). The same is observed for pipelines. Both the natural gas and hydropower systems are flexible enough to handle these seasonal differences.*

8.2 Challenges for the hydropower system

The potential to use Norwegian hydropower to provide flexible energy and for balancing services is based on the use of existing reservoirs to avoid large environmental impacts by creating additional hydro storage capacity. Due to the need for seasonal storage, Norway has a large hydro reservoir capacity and there is never a lack of free capacity in the reservoirs as long as they are used for short-term storage and balancing.

When considering the volumes suggested by the EMPIRE analysis in the 2050 system, net exchange rates range from 30GWh/h exports in the Baseline scenario (the double in the NoCCS scenario) to net imports within the same day. This will require massive investments in cable.

Challenge: While these are profitable for Europe as suggested by the analysis, it is the market design and the pricing of this flexibility that will decide if they are also profitable for Norway.

The EMPIRE model does not consider if this flexibility is feasible from an environmental perspective. Such studies have been made by the HydroBalance project[31]. Results suggest that to make Norwegian hydropower this flexible without environmental impact, it will most likely be necessary to increase the generation capacity, use existing reservoirs and install pumping capacity. Pumping and new tunnels allow the use of existing reservoirs within current concession limits of highest and lowest water levels.

Challenge: More research is needed to investigate under which conditions in terms of investment costs and market design such investments in generation and pump capacity would be profitable.

Building capacity to provide this flexible energy and balancing services will not be riskless. The Third Energy package (EC, 2007) addressed the issue of how to stimulate market competition but did not address the issue of whether the market offered the necessary incentives to invest in generation, distribution and transmission and storage capacity in a system with greater shares of renewables. How the EU is addressing these concerns is important for Norway's opportunities as a provider of flexible energy in the hourly, weekly and seasonal horizon.

The cable capacity necessary to support import/export is highly scenario dependent. If CCS technology is not available, the EMPIRE studies suggest that power exports from Norway would almost double, mostly due to increased utilisation of offshore wind resources. Under

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[31] HydroBalance project: Graabak, I., Jaehnert, S., Korpås, M., & Mo, B. (2017). Norway as a Battery for the Future European Power System—Impacts on the Hydropower System. Energies, 10(12), 2054.

such demand, technology and policy uncertainty, long-term agreements between private parties or between countries would be necessary. The need for this capacity, as well as flexibility in energy provision and for balancing services must be seen in relation to how the national generation and transmission systems are built in European countries. While we see more and more market integration in energy-only markets, and even balancing markets, countries still seem to invest in their national systems driven by self-interest. We do not believe that market participants alone will have the strength to secure the needed development for new generation and for capacity in cables from Norway to the rest of Europe, unless policy uncertainty is reduced.

Challenge: It is doubtful if investments of this size would happen under today's policy uncertainty. Long-term agreements should therefore address the division of costs, revenues and risk between the participants in the relevant value-chains and between the relevant countries.

The installation of new cables between countries, as well as the provision of balancing services, flexible energy and capacity services must be priced. It would be natural for the buyer of the services to pay for the cost as a minimum. However, the benefit from the services may be far higher than the cost of providing them. In this case, the profit sharing will be negotiable.

For example new cables can provide value simultaneously to different stakeholders like generation companies, system operators, grid owners and customers in both the originating country and the importing country, but this is not always the case when building a new cable between two countries. Hence, there are challenges in terms of distributing costs, revenues and risks of investments. There are considerable investment costs for large-scale upgrades of the electricity transportation systems. When it comes to reserves and capacity markets, the costs are often high compared to the energy volumes involved.

Challenge: It will be necessary to decide on tariffs both for direct transmission of power between countries, for cross-border transit and for cable reserved for balancing or capacity services. This is directly linked to the division of costs, revenues and risk mentioned above.

For the reserve capacities and balancing services in the short run, these considerations are crucial as they depend on additional capacity that is not needed for Norwegian energy export/import or generation. Hence it requires that someone else needs it. The energy volumes involved are small, while the cost of reserving capacity is potentially high. Typically, this will be extra power installed at the generation side and extra cable capacity. Uncertainty is somewhat reduced by the fact that the extra power and cable can be used both for balancing services and for hourly or weekly energy exchange.

Challenge: We need to understand better how to allocate capacity in the cables and how to price that capacity if this volume of cables should be investable.

This can also be seen in relation to current efforts of promoting national capacity mechanisms/markets, often referred to as Capacity Remuneration Mechanisms (CRMs). If introduced nationally and uncoordinated, CRMs are a risk to the progress of cross-border market integration and competition in Europe.

Challenge: This is a major governance challenge that must be addressed actively by Norwegian stakeholders concerned with the provision of flexible energy services to Europe.

Traditionally, Norwegian consumers have taken the cost of grid investment. It can be argued that this is fair as it has been to the benefit of the consumers through increased security of supply and more stable prices.

Challenge: The more focused the cable system is on net export or service provision, the more difficult it is to argue that Norwegian consumers should pay for the cost.

8.3 Challenges for the natural gas system

The variation in the consumption patterns illustrates how natural gas from the Norwegian pipeline system can be an important flexibility provider for the European power market. Our analysis of variation here shows that the capacity of the line pack storage in the pipelines will be able to handle this challenge.

Challenge: The use pattern for natural gas in 2050 is highly dynamic and will require the commercial development of flexible services for pipeline storage and the prioritising of ramping capabilities for natural gas power plants with and without CCS are when developing new technology. The central issue will be flexible natural gas value chains.

Another interesting observation in the EMPIRE study is that with CCS technology in place, the demand for natural gas in the power sector in 2050 will be almost double in the Baseline scenario as compared to the NoCCS scenario. With CCS technologies, natural gas will also be used as baseload in some seasons.

9 Recommendations

Our analysis shows that Norway can contribute to the European flexibility and storage needs with both hydropower and natural gas at many different time horizons. Hydropower can be used for providing flexibility in most time horizons from seconds up to seasons.

9.1 Renewable energy

If Norway wants to take a larger role as a provider of flexibility, more investments in HVDC[32] cables to Europe are needed. To fully utilise the Norwegian resources, European cooperation on investments in the energy system needs to be increased. Through the Energy Union, cooperation on market integration in intraday and spot markets and to some degree short-term balancing markets increases, but investment decisions by individual countries still tend to be based on national interests related to welfare, jobs or security of supply. For countries like Norway which would invest to provide energy or services for other countries, that creates policy uncertainty related to the demand for the products. That policy uncertainty could prevent full utilisation of the Norwegian resources, as potential investors face uncertainty on the demand side coming from political choices rather than from the markets.

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[32] HVDC: High-voltage, direct current (høyspent likestrømsoverføring)

We recommend entering into EU-wide collaboration agreements or multilateral agreements between countries in order to reduce uncertainty by addressing the division of costs, revenues and risk between the participants in the relevant time-horizons.

Capacity markets[33] for generation can be used to promote coordinated investments. **We recommend** Norway to take an active role to ensure that these markets are coordinated and not introduced nationally. This is a major governance challenge that must be addressed.

In order to provide balancing services in the very short run, capacity must be reserved in cables and in generation. The trade-off related to using the capacity for energy exchange instead must be considered in pricing of such services, reflecting that the energy volumes are small but the value high.

- If capacity is going to be built to provide more of this short-term flexibility, **we recommend** cross-border markets for such services to be further developed and secured in the long run.
- **We recommend** decisions on tariffs to be used both for direct transmission of energy between countries and for cross-border transit as well as for system services mainly established to provide flexibility in the very short run. There is a policy risk involved here because these tariffs are linked to risk, revenue and cost sharing.

The full utilisation of Norwegian renewable resources requires more cables for import/export and a strengthening of the Norwegian grid. Traditionally, Norwegian consumers have taken the cost of grid investment. It can be argued that this is fair for parts of the infrastructure investments needed for domestic offering of balancing services and reducing security of supply issues. Parts of this new capacity will most likely benefit the consumers through increased security of supply and more stable prices.

On the other hand, when it comes to net export of energy, capacity services and balancing services provided to other countries, it is more difficult to argue that Norwegian consumers should cover the cost. **We recommend** the development of a new regime for cost distribution related to the building of new cables with this purpose if the Norwegian renewable potential is to be fully utilised.

9.2 Natural gas in the power system

Our studies show that without CCS, natural gas may still play a major role in the power sector in 2030 and 2040, but in 2050, the volume of natural gas used by the power sector in the NoCCS scenario is only half of the volume suggested if CCS is successful as a commercial technology.

Natural gas with CCS somewhat reduces the share of renewables in the generation mix but provides system benefits:

- The availability of CCS reduces the need for over-investments in renewables, which tend to cause substantial amounts of curtailed generation, even when inexpensive energy storage and demand response measures are available as investment options.
- The need for transmission investments is reduced, saving system costs and thus reducing consumer prices.
- Controllable generation capacity in the system will increase security of supply.

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[33] In a capacity market, suppliers are required to have enough resources to meet their customers' demand plus a reserve amount.

We recommend further support of the commercialization of CCS value chains in order to secure the use of Norwegian natural gas as a flexibility source for the European power system.

We recommend more research directed towards developing flexible power generation technologies for natural gas with CCS.

We recommend Norway to take an active stance in identifying viable pathways for further development for natural gas in Europe where new services, business models, commercial terms and legislation are needed to promote flexibility services in the pipeline system and value chain is prioritised.