SINTEF

TR A7200 - Unrestricted

Report

Large scale exchange of balancing power between Norway and Europe –analysis of impacts.

Author(s)
Ingeborg Graabak
Hans Ivar Skjelbred

SINTEF Energy Research
2012-05-10

CEDREN – Centre for Environmental Design of Renewable Energy: Research for technical development and environmental impact of hydro power, wind power, power lines and implementation of environment and energy policy.

SINTEF Energy Research, the Norwegian Institute for Nature Research (NINA) and the Norwegian University of Science and Technology (NTNU) are the main research partners. A number of energy companies, Norwegian and international R&D institutes and universities are partners in the project.

The centre, which is funded by The Research Council of Norway and energy companies, is one of eleven Centre for Environment-friendly Energy Research (FME). The FME scheme consists of time-limited research centres which conduct concentrated, focused and long-term research of high international quality in order to solve specific challenges in the field of renewable energy and the environment.

SINTEF

SINTEF Energi AS
SINTEF Energy Research

Address:
Postboks 4761 Sluppen
NO-7465 Trondheim
NORWAY

Telephone:+47 73597200
Telefax:+47 73597250

energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

KEYWORDS:
Future power system
Pump-storage
hydro power
RES based power
production

Report

Large scale exchange of balancing power between Norway and Europe –analysis of impacts.

VERSION	DATE
1.0	2012-05-10

AUTHOR(S)
Ingeborg Graabak
Hans Ivar Skjelbred

CLIENT(S)	CLIENT'S REF.
Research Council of Norway	

PROJECT NO.	NUMBER OF PAGES/APPENDICES:
12X757	39

ABSTRACT
This report is from a study in Centre for Environmental Design of Renewable Energy (CEDREN). The objective of the analysis is to show the impacts on the European power system if Norwegian hydropower is used for large-scale balancing. A special focus is on possible reductions of the CO_2 emissions.

A scenario methodology is used to explore different future developments of the power systems. The analysis is performed by the EMPS- model. All expected impacts on the European power system where observed: the Norwegian hydro power system worked as a pump-storage, the surplus in the production, the rationing of the demand and the CO_2 emissions from the European power production were reduced.

However, this report must mainly be regarded as a preliminary analysis of the impacts of Norway as a "green battery" for Europe. The work has given increased insight in necessary improvements in the design of the cases for analysis, the use of the EMPS as well as the implementation of the model before it is possible to finally quantify the impacts. The work will be brought further in other projects.

PREPARED BY Ingeborg Graabak	SIGNATURE J. G.
CHECKED BY Bjørn H Bakken	SIGNATURE
APPROVED BY Magnus Korpås	SIGNATURE MK

REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
TR A7200	978-82-594-3520-0	Unrestricted	Unrestricted

Document history

VERSION	DATE	VERSION DESCRIPTION
Version 1.0	2012-05-10	

Table of contents

APPENDICES

[List appendices here]

1 Introduction

1.1 Background

This study is carried out within Centre for Environmental Design of Renewable Energy (CEDREN). CEDREN is one of the Centres for Environment-friendly Energy Research (CEER) in Norway that was formed as a direct response to the political agreement for a substantial increase in the research and development in the fields of renewable energy in Norway. CEDREN is funded by the Norwegian Research Council and the Energy Industry.

The main objective of CEDREN is to develop and communicate design solutions for renewable energy production that address environmental and societal challenges at local, regional, national and global levels. More specifically, the research is focused on hydro and wind power production and power transmission systems.

One of the activities in CEDREN is to investigate opportunities and challenges for using Norwegian hydropower as large-scale balancing power for Europe, working like a "green renewable battery" for Europe. Norway is Europe's largest producer of hydropower with almost 30 000 MW installed capacity, and an annual production of approximately 123 TWh. The reservoir storage capacity is about 85 TWh, half of the total capacity in Europe. The system is characterised by a highly flexible capacity – i.e. in only a few minutes a hydropower plant is regulated from standstill to full load.

Both national and international climate goals generate a great demand for more renewable energy. Phasing in more unregulated renewables, such as on- and offshore wind turbines, photovoltaic power and unregulated hydropower creates a great need for more balancing power.

Balancing power shall in this context be understood as exchange of electricity in both short and long periods and on short notice. The minimum time resolution in this analysis is one hour, but in a real system balancing power will be exchanged in even smaller time intervals. The exchange of electricity will in most cases go in both directions and sum up to be approximately zero over a longer period, e.g. over years. Seen from the perspective "Norway as a green battery for Europe", Norway will import electricity in periods with production surplus in the rest of Europe because of high production from intermittent resources like wind or the solar. The imported electricity may be used to pump up water to higher reservoirs (charging of the battery). When the wind and the sun production are limited, the production in the hydro power system will be increased and Norway will export "balancing power" (discharging of the battery).

1.2 Objective of study

The objective of the analysis documented in this report is to show the impacts on the European power system when Norwegian hydro power is used as a "green battery". A special focus is on possible reductions of the CO_2 emissions. The analysis is built upon work done in the EU project SUSPLAN [SUSPLAN, D7.2] and in another CEER, Zero Emission Building (ZEB) [Graabak, 2011].

2 Terminology

2.1 Abbreviations

CSP	-	Concentrated Solar power
EMPS	-	European Multi-area Power Market Simulator
HVAC	-	High Voltage Alternating Current
PV	-	Photovoltaic
RES	-	Renewable Energy Sources
WEO	-	World Energy Outlook
ZEB	-	Zero Emission Building

2.2 Country codes

BE	-	Belgium
DE	-	Germany
GB	-	Great Britain
LT	-	Lithuania
NL	-	The Netherlands
NO	-	Norway
SE	-	Sweden

3 Description of methodology

A scenario methodology is used to explore different future developments of the Norwegian and the European power systems. The scenarios are described in section 3.2. The analysis is performed with the EMPS- model, see section 3.1. The input data set used in the analysis is described in section 3.3.

3.1 EMPS – A European Multi-area Power Market Simulator

The analysis is performed with the EMPS – a European Multi-area Power Market Simulator, see Figure 3-1. The EMPS model is a stochastic optimization model for hydro-thermal electricity markets widely used for price forecasting, corporate and governmental energy system planning and production scheduling [Wolfgang, 2009].

Electricity prices balance demand and supply at all times in the model, see Figure 3-2. There are several options for balancing the market in an area, e.g. non-dispatchable renewable production (sun, wind, ...), hydropower, thermal power (coal-power etc), import/export and reduced demand, etc. Renewable production plants are described by their capacities, and are regarded to have no variable costs. The stochastic nature of sun and wind resources is represented by data sets with many years of measured radiation or wind. Thermal power plants are mostly described by their capacity and marginal production costs that include fuel costs and CO_2 emission permit costs. For hydropower the availability of water is a limited resource. Since reservoirs can be used to store water there are considerable time-couplings. In addition there is a stochastic problem due to the stochastic nature of inflow.

The EMPS model requires a large amount of input data for a detailed representation of the electricity market. The power system under consideration is divided into a number of interconnected areas. Each area represents a European country or an offshore wind production site connected to a country. The inputs to the model include among other costs and capacities for generation, transmission and consumption of electricity and information about weather variables in the past.

Figure 3-2 illustrates the equilibrium between demand and supply given by the intersection between the respective curves. The continuous increase in marginal costs for regulated hydropower reflects the increasing water values at lower reservoir fillings.

The EMPS model may be simulated with several storage possibilities per node. For each time step and for each node/area there is calculated an energy balance (GWh) with production from conventional plants like nuclear, hard coal, lignite, natural gas and oil. Several renewable production possibilities may be available like hydro, wind, solar, biogas, wave and solid bio. Through transmission capacities to other nodes/areas there will be power exchange (export/import). Pumping, curtailment and surplus will also be a part of the energy balance. Surplus is energy produced but not possible to sell, because there is not enough demand at the time.

In addition to the electricity balance, CO_2 emissions (metric tons of CO_2 equivalents) and the marginal power price (Euro/MWh) are reported from EMPS.

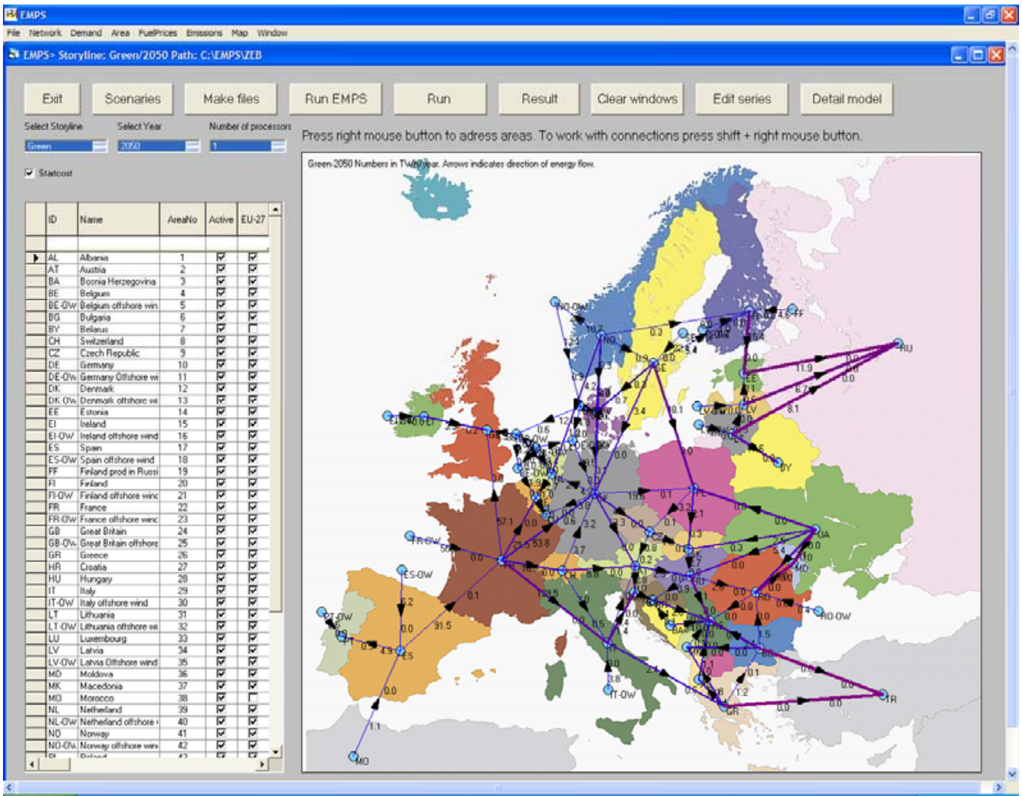

Figure 3-1 EMPS – A European Multi-area Power Market Simulator

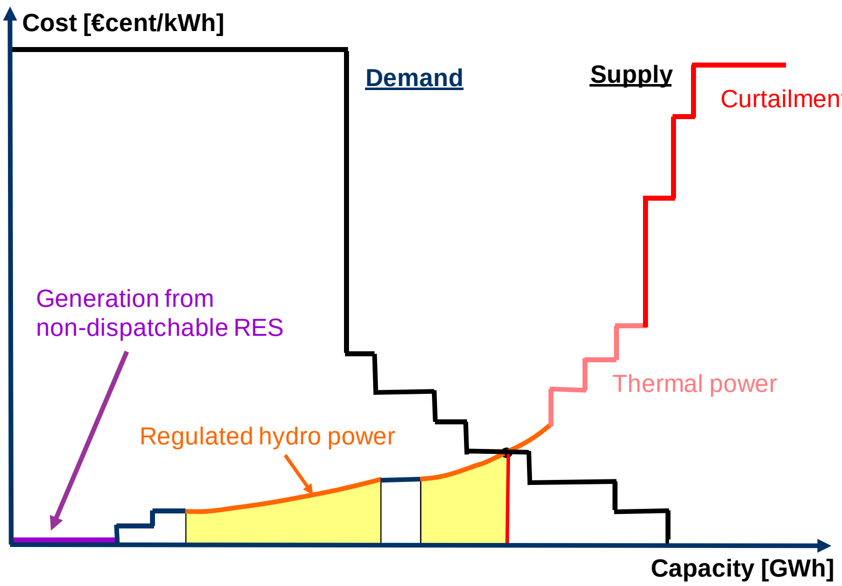

Figure 3-2 Calculation of market balance (per area and time step)

3.2 The scenarios

The analyses in this project are based on the so-called Blue scenario in the SUSPLAN [Susplan, 7.2] and the ZEB analyses [Graabak, 2011]. To be able to understand the Blue scenario in a context, this report includes a short description of all scenarios from the SUSPLAN and the ZEB analysis.

The SUSPLAN scenarios include each European country in a period up to 2050. In all the scenarios it is assumed that there is a strong political intent in Europe to promote sustainable development and security of supply in the energy sector. This strong political intent results in the use of necessary incentives and regulations for increased deployment of Renewable Energy Sources (RES) generation technologies.

The scenarios are located on a coordinate system between two axes depicting decisive factors with regard to RES development: The y-axis represents Public Attitude (to environmental issues and renewable energy), ranging from an indifferent to a positive attitude, and the x-axis stands for the speed of Technology Development. These two axes are used to span out a set of 4 relevant futures as a common background for scenario analysis, as shown in Figure 3-3.

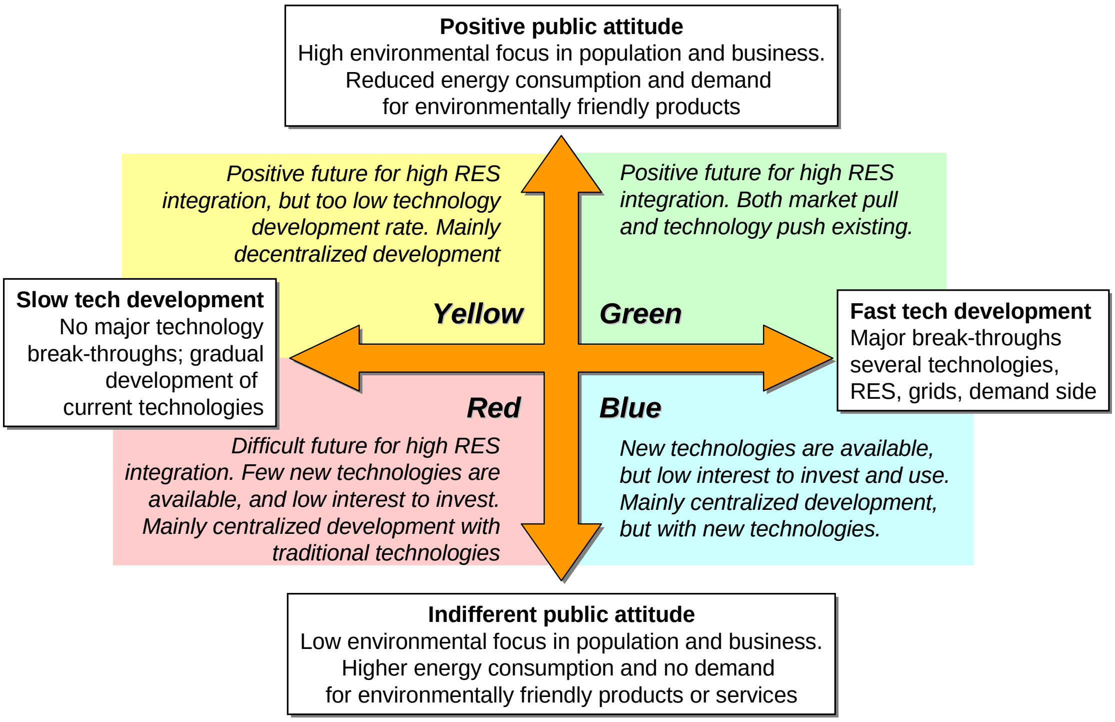

Figure 3-3 Scenarios defined within the SUSPLAN project

Public attitude is of particular importance when it comes to the realization of RES-projects, the diffusion of distributed RES-generation and energy efficiency technologies as well as the implementation of grid extensions or, for example, smart grid applications in households. Only if there is a broadly positive public attitude towards renewable energies will the population push the development towards a sustainable energy system by adopting the available technologies and accepting changes to the energy system with all their associated consequences (e.g. changes to the landscape or in electricity tariffs).

This is reflected in the Green and Yellow scenarios in which a positive public attitude allows high shares of RES-generation to be reached, of which a large part can be attributed to distributed generation, for example PV installations. The high public awareness in these scenarios also implies a lower energy demand compared to the other scenarios due to a change in consumer behaviour in terms of energy saving and the application of the available energy efficiency technologies, see Figure 3-4.

In contrast, in the Blue and Red scenarios, the public has an indifferent attitude towards RES and opposition to RES-projects and grid expansions remains high and hinders developments in these fields.

Thus the introduction of RES-technologies, as far as these are technologically available, takes place only on a government-driven, “top-down” level.

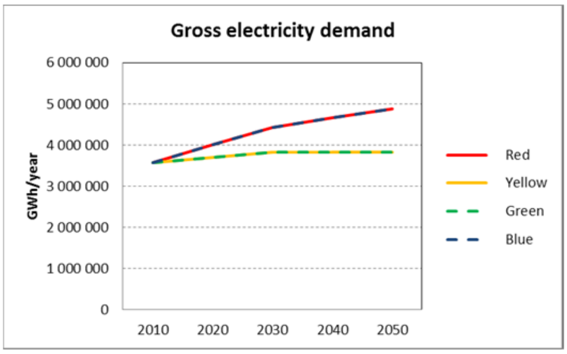

Figure 3-4 Development of electricity demand in Europe in the SUSPLAN scenarios

The technological development, on the other hand, is the key factor determining whether RES- and energy efficiency technologies as well as innovative storage, transmission and smart grid appliances are available on the market and which costs are related to their introduction.

In the Green and Blue scenarios the development of these technologies is highly advanced and a multitude of generation, transmission and smart grid technologies are available for project developers and consumers. In the Green scenario, where these are combined with a positive public attitude, this leads to the most sustainable development with high shares of RES being realized based on a multitude of proven and innovative RES technologies. In the Blue scenario, although the same technologies are available, low public acceptance results in mainly centralized technological solutions like, e.g. large Concentrated Solar Power, hydro or offshore wind power units. Local, distributed generation does not meet with public approval and thus cannot be realized on a large scale. In the Yellow and Red scenarios, by contrast, slow technology development hinders the penetration of innovative RES, energy efficiency and transmission solutions and thus limits the possible RES portfolio to a smaller number of basically proven and mature technologies, see Figure 3-5.

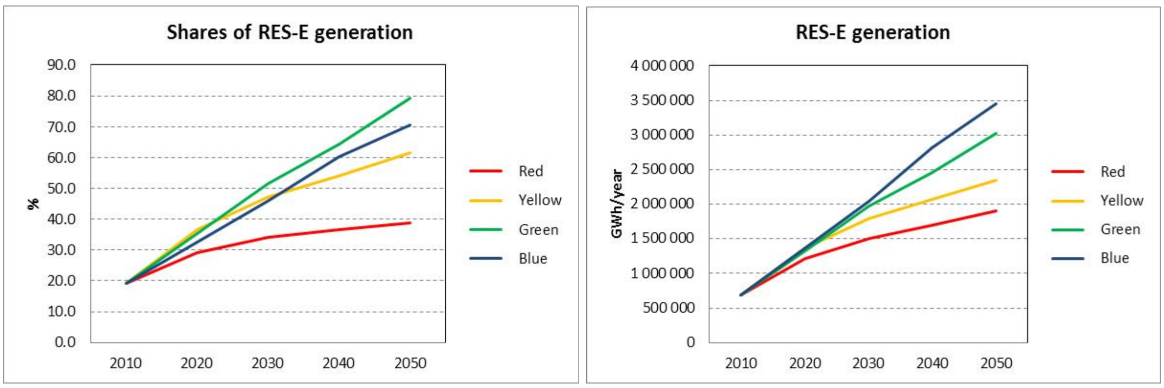

Figure 3-5 Development of RES electricity generation in Europe up to 2050

The SUSPLAN scenarios are described in more detailed in [Susplan, D1.2].

The most relevant scenario for analyses of Norway as a "green battery" for Europe is assumed to be the scenario with the highest volume of intermittent renewable production. This is the Blue scenario, and Blue is chosen for further studies. The Blue scenario is described in more detail in section 3.2.1. However, compared to the Blue scenario in the SUSPLAN and the ZEB projects, there is used a lower level for hydro power capacities in 2040 and 2050 in Europe in the CEDREN analysis.

3.2.1 Description of the Blue scenario

General description

There have been many breakthroughs in technology for energy efficiency and for renewable energy production.

However, the public is rather reluctant to change their behaviour in an environmentally friendly direction, and few investors and industries are interested in energy technologies and advanced building solutions. The development towards a more sustainable world is driven by regulations and incentives from the authorities.

Electricity consumption

Due to limited interest among the public, energy consumption is increasing in all sectors. A lot of new technologies are available for energy efficiency, but the deployment of the technologies are limited.

In the building sector, new and very energy efficient materials and solutions for building construction are available at competitive cost. This has enabled regulators to set good efficiency standards for both new construction and renovation.

New constructions are built to regulation standard for new buildings, and only a small share has higher efficiency. Renovation level is driven only by ageing of the stock (not by energy conservation). However, when renovation occurs, energy performance is improved to regulation standard for renovated buildings (different from new buildings). This holds true for all buildings: residential, public, commercial and industry.

Advanced HVAC, smart metering, control equipment, energy efficient appliances and advanced technology for on-site production are also available, but the low public interest result in limited deployment.

Electricity production

Development of the energy system is mainly driven by authorities and have in most cases resulted in large-scale centralised solutions. However, both technology development and efficient quota mechanisms have reduced emissions from fossil energy considerably. Among others, huge volumes of renewable energy may be produced based on ocean energy (wind, wave and tidal energy).

The yearly production from renewable energy is also considerable increased in Norway and Sweden. However, specific effects of the "Green-certificate" arrangement running until 2020 are not studied.

There have been several breakthroughs regarding transmission technology. Transmission capacities between regions and countries are very high, so major parts of Europe may be considered as a highly integrated electricity market.

3.3 The input data sets

3.3.1 Overview of the data set

In the CEDREN analysis the European power system is modelled with 55 areas (countries/regions etc) and 97 interconnections between the areas. There are 15 offshore wind areas. To be able to simulate the uncertainty in inflow to hydro power plants and reservoirs, the wind available at wind production sites and the radiated energy of the sun available for PVs or CSP, there is used up to 75 years with statistical data for each area. The demand is considered to be inflexible in each price period (although curtailment of the demand is modelled), so variations in the production portfolio and export/import are used to balance the market. The model also includes a single storage subsystem per node.

Below is a description of the input data set for the SUSPLAN and the ZEB analyses. It is described how the data sets are established for all four scenarios, even though only the Blue scenario is used in the analysis for CEDREN.

Different sources are used for quantification of the input parameters to the EMPS analysis. The most important input parameters from the SUSPLAN and the ZEB analysis are:

- RES-electricity deployment
- Final electricity demand development
- Development of fossil fuel-, CO2- and biomass prices

In the following, the empirical settings of several of the key parameters are presented and the most relevant references/sources and own assumptions are briefly explained.

3.3.2 RES-Electricity Deployment until 2050

For each of the four different scenarios four different empirical sets of future developments for RES-electricity generation as a share of final total electricity demand are determined on aggregated European level up to 2050. Figure 3-5 present RES-Electricity deployment scenarios on aggregated European level up to 2050 (Source: Green-X modelling results up to 2030 [Faber, 2007], [Auer, 2008]; extrapolated up to 2050 according to the long-term RES-Electricity potentials and ambitions in energy efficiency in the different European counties).

3.3.3 Final Electricity Demand until 2050

Similar to future RES-electricity deployment the same sets have been established also for total final electricity demand for each of the scenarios on aggregated European level up to 2050. Figure 3-4 presents final electricity demand (Source: Primes model runs up to 2030 [Capros, 2005]; extrapolated to 2050).

3.3.4 Fossil Fuel-, CO_2- and Biomass Prices until 2050

A consistent set of relevant prices for fossil fuels, CO_2 and biomass need to be part of the starting point for the analysis of future electricity market development.

After evaluation of several international studies, the future price trajectories of the Reference Scenario and 450 ppm Scenario of the World Energy Outlook [IEA, 2009a] were chosen for the SUSPLAN project. The two different price scenarios of the WEO2009 are implemented according to the expected demand and importance of fossil and CO_2 products in the different scenarios. As the demand patterns of the scenario two couples Red/Blue and Yellow/Green are similar, the four different scenarios are combined to two scenario-clusters (see Figure 3-6).

- **Yellow/Green**: Due to lower demand of fossil fuels and decreasing importance of CO_2 instruments, the low price path of each of the two price scenarios of the WEO [IEA, 2009a] is used.
- **Red/Blue**: Due to still high demand of fossil fuels and still high importance of CO_2 instruments, the high price path of each of the two price scenarios of the WEO [IEA, 2009a] is used.

Positive Public Attitude

WEO2009 "450 ppm Scenario" ($2008 Prices)	2008	2015	2020	2025	2030	2035	2040	2045	2050
IEA crude oil imports ($/bbl)	**97,2**	**86,7**	**90,0**	**90,0**	**90,0**	**90,0**	**90,0**	**90,0**	**90,0**
Natural gas imports ($/Mbtu PCS)	10,3	10,5	11,0	11,0	11,0	11,4	11,4	11,4	11,4
Natural gas imports ($/Mbtu PCI)	11,5	11,6	12,3	12,3	12,3	12,3	12,3	12,3	12,3
Natural gas imports ($/MWh PCI)	**39,2**	**39,7**	**41,9**	**41,9**	**41,9**	**41,9**	**41,9**	**41,9**	**41,9**
OECD steam coal imports ($/t)	120,6	85,6	80,1	72,5	64,8	57,2	49,6	41,9	34,3
OECD steam coal imports ($/MWh)	**16,5**	**11,7**	**10,9**	**9,9**	**8,8**	**7,8**	**6,8**	**5,7**	**4,7**

Lower demand of Fossils in Yellow/Green than Red/Blue -> Lower Price Level

WEO2009 "Reference Scenario" ($2008 Prices)	2020	2030	2040	2050
CO_2 Price [$/tCO_2$]	**43**	**54**	**65**	**76**

Public adapts production and consumption of energy themselves in a sustainable way; CO_2 market less important instrument and, therefore, prices are lower

Slow Techn. Develop. ← → **Fast Techn. Develop.**

WEO2009 "Reference Scenario" ($2008 Prices)	2008	2015	2020	2025	2030	2035	2040	2045	2050
IEA crude oil imports ($/bbl)	**97,2**	**86,7**	**100,0**	**107,5**	**115,0**	**122,5**	**130,0**	**137,5**	**145,0**
Natural gas imports ($/Mbtu PCS)	10,3	10,5	12,1	13,1	14,0	15,0	15,9	16,9	17,8
Natural gas imports ($/Mbtu PCI)	11,5	11,6	13,5	14,6	15,6	16,7	17,7	18,8	19,8
Natural gas imports ($/MWh PCI)	**39,2**	**39,7**	**45,9**	**49,7**	**53,2**	**56,8**	**60,4**	**64,0**	**67,6**
OECD steam coal imports ($/t)	120,6	91,1	104,2	107,1	109,4	112,0	114,5	117,0	119,5
OECD steam coal imports ($/MWh)	**16,5**	**12,4**	**14,2**	**14,6**	**14,9**	**15,3**	**15,6**	**16,0**	**16,3**

Higher demand of Fossils in Red/Blue than Yellow/Green -> Higher Price Level

WEO2009 "450 ppm Scenario" ($2008 Prices)	2020	2030	2040	2050
CO_2 Price [$/tCO_2$]	**50**	**100**	**125**	**150**

High CO_2 market price is important instrument (for authorities) to influence production and consumption of energy (due to indifferent „public")

Indifferent Public Attitude

Figure 3-6 Expected development of the fossil fuel (crude oil, natural gas, coal) and CO_2 prices up to 2050 in the Red/Blue and Yellow/Green scenarios in SUSPLAN

In SUSPLAN scenario analyses it is assumed that there will be a common European market for biomass in the medium- to long-term, resulting in a converging international biomass wholesale price. Derived from the RES2020 project [RES2020], where several relevant country-specific biomass fraction and cost data are available for all EU Member States (incl. Norway and Switzerland), an average biomass price of €6 per GJ is taken as starting point for 2010 for several of the four scenarios. Moreover, roughly 80% of the biomass cost values in the different countries are within a range of €2 to €9 per GJ, with a decreasing trend for moderate biomass use towards the future. In the SUSPLAN scenario context the empirical settings of the biomass wholesale prices up to 2050 have been set as follows. Due to the fact that in the Red scenario demand for biomass is assumed to be the lowest (compared to other scenarios), a linear price decrease from €6 per GJ in 2010 to €5 per GJ until 2050 is foreseen. In the Blue scenario demand on biomass is somewhat higher than in Red and, therefore, a constant biomass price of €6 per GJ remains until 2050. In the two other scenarios, Green and Yellow, demand on biomass is significantly higher and, therefore, increasing biomass wholesale prices are expected until 2050 reaching price levels of €8 per GJ and €10 per GJ for Green and Yellow respectively.

SINTEF

3.3.5 Transmission capacities

For the CEDREN analysis the transmission capacities between countries are mainly based on data from [ENTSO-E, 2012]. The most important capacities relevant for the analysis are shown in Table 3.1.

Table 3.1 Assumed transmission capacities [MW]

Country codes	Transmission capacity
NO-SE	5150
NO-DK	1650
NO-NL	700
NO-DE	1000
NO-GB	1000
SE -LT	700
GB-OW - BE-OW	20000
GB-OW - NL-OW	20000
GB-OW - DE -OW	20000

For explanation of country codes see section 2.2. Nodes marked "OW" are offshore wind nodes. As shown in the table there is assumed an offshore grid in the North Sea. The connection between each offshore wind farm and the country to which it belongs, is set large enough to not cause any congestion.

3.3.6 Other input data to the analysis

Non-RES capacities like nuclear, coal and gas production capacities are from [Eurelectric, 2009] which gives expected development per country up to 2030. Non-RES capacities from 2030-2050 are extrapolations based on the development from 2010-2030. German nuclear capacities are assumes to be available in 2030. In 2050, however, all German nuclear units are removed from the simulations.

4 Description of the different cases simulated

Based on the Blue scenario from the SUSPLAN and the ZEB projects, four different cases have been simulated to investigate the impact of Norwegian balancing power:

1. "2030-1572": the analyses are based on the Blue data for 2030 and a pumping capacity in Norway of 1572 MW. The transmission capacities are shown in Table 3.1
2. "2030-10000": the analyses are based on the Blue data for 2030. In addition the capacity of the Norwegian power system is increased with 10 000 MW at the same time as the time of use for the system is reduced correspondingly such the system produces the same volume of energy as before. Further, the pumping capacity is increased with 10 000 MW to a total of 11572 MW. The transmission capacity between Norway and Great Britain, Germany and the Netherlands are increased with 20 000 MW
3. "2050-1572": the analyses are based on the Blue data for 2050 and a pumping capacity in Norway of 1572 MW. The transmission capacities are shown in Table 3.1.
4. "2050-10000": the analyses are based on the Blue data for 2050. In addition the capacity of the Norwegian power system is increased with 10 000 MW at the same time as the time of use for the system is reduced correspondingly such the system produces the same volume of energy as before. Further, the pumping capacity is increased with 10 000 MW to a total of 11572 MW. The transmission capacity between Norway and Great Britain, Germany and the Netherlands is increased with 20 000 MW

Table 4.1 Assumed transmission capacities in the cases "2030-10000" and "2050-10000"

Country codes	Transmission capacity
NO-SE	5150
NO-DK	1650
NO-NL	7367
NO-DE	7667
NO-GB	7667
SE -LT	700
GB-OW - BE-OW	20000
GB-OW - NL-OW	20000
GB-OW - DE -OW	20000

5 Results

5.1 Cases "2030-1572" and "2030-10000"

Below are the results for the simulations for 2030 described. The results are given for the following group of countries: EU27, Norway, Switzerland and all countries on the Balkans.

5.1.1 Energy balances and emissions

From Table 5.1 we can see some of the main impacts of changing the power system from case "2030-1572" to "2030-10000". A few TWh of excess wind energy can be recovered through pumping units. The overall reduction in CO_2 emissions is approximately 10 Mtonne per year. As a comparison, in 2009 Norway emitted 42.8 Mtonne CO_2 [Miljøstatus, 2012]. The reduction is equal to 1.1 % of the total CO_2 emissions from electricity generation in Europe in the simulated areas.

Table 5.1 Summarized results for case "2030-1572" and "2030-10000" at European level

		"2030-1572"	"2030-10000"	"2030-10000"-"2030-1572"
CO2 emissions	[Mtons/year]	936	925	-10
Curtailment	[GWh/year]	3 858	3 751	-107
Dumping	[GWh/year]	8 034	4 696	-3 338
Lignite prod	[GWh/year]	76 921	74 944	-1 977
Coal prod	[GWh/year]	637 536	634 874	-2 662
Gas prod	[GWh/year]	687 994	673 080	-14 914

As these reductions appear due to less use of fossil fuels, Figure 5-1 shows how this is balanced by other parts of the electricity system. As shown in the figure only a limited part of the change is reduced transmission losses and dumping. A large share is increased production from bio energy. The bio energy production is increased because prices in among other Sweden increases as a result of increased transmission capacity to Germany through Norway. This is further discussed in section 6.2.

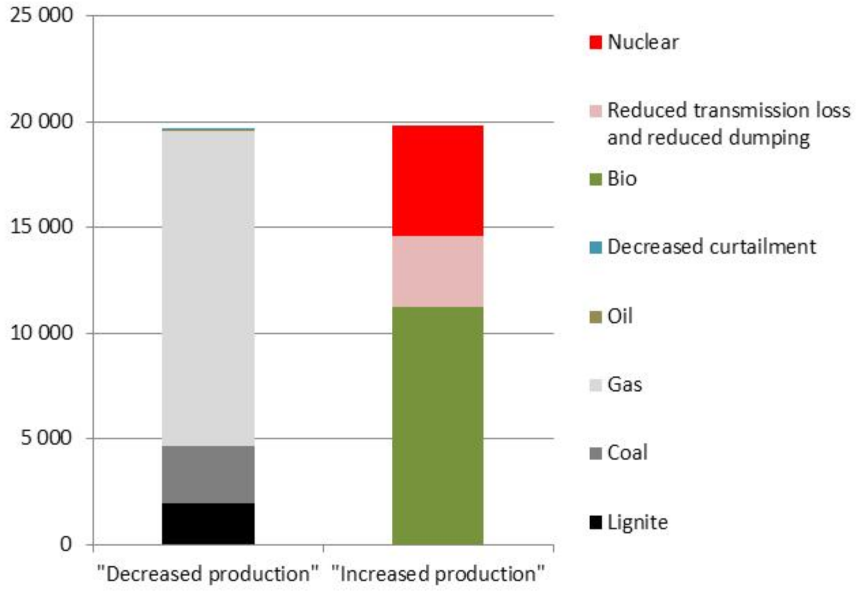

Figure 5-1 Main changes in electricity balance from case "2030-1572" to "2030-10000" [GWh/year]

The shares for different technologies and the balance between demand and total supply for each country are illustrated in Figure 5-2.

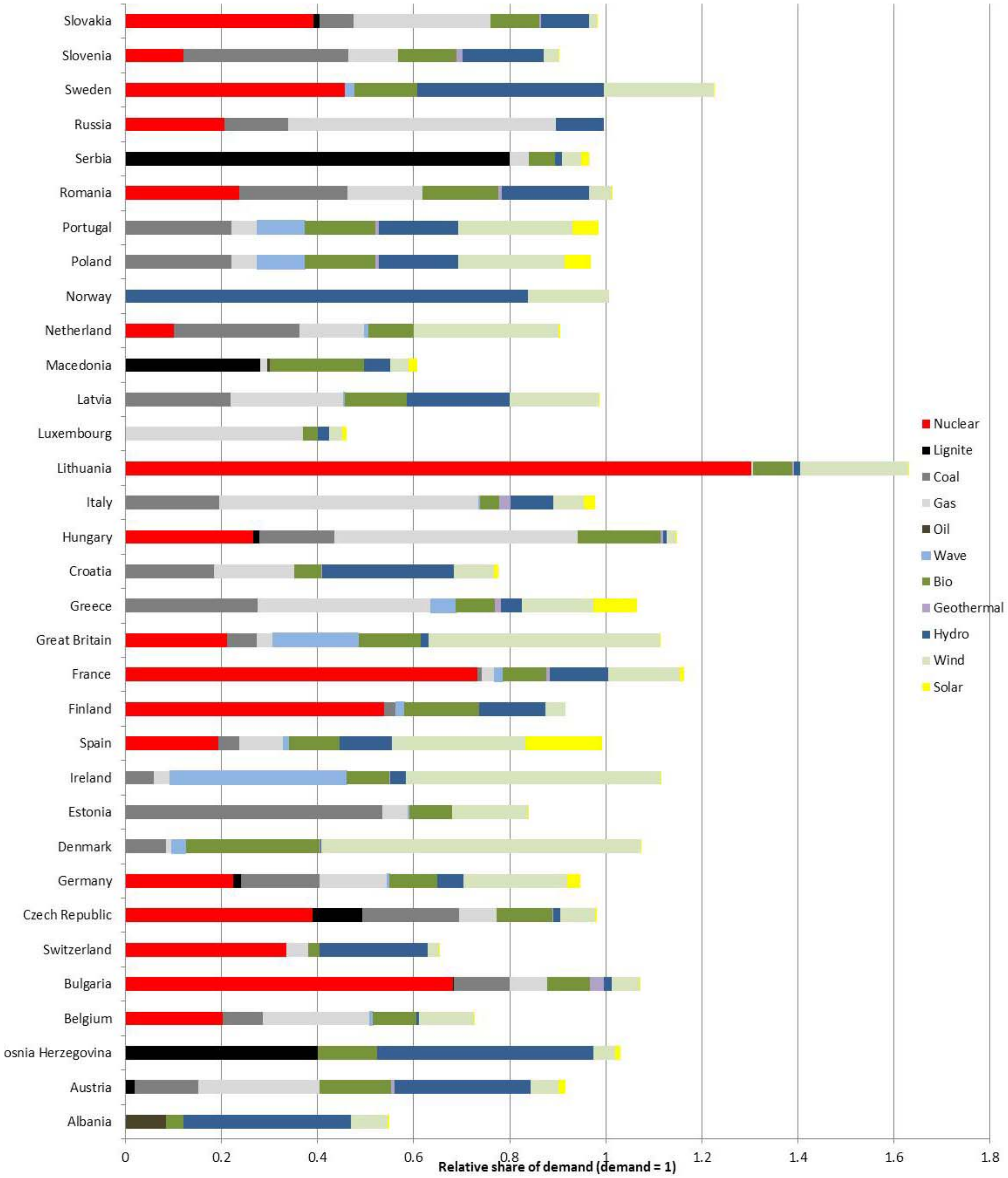

Figure 5-2 Electricty production per source in share of demand per country for case "2030-1572"

As Figure 5-2 only shows relative values, Figure 5-3 shows the actual energy balance for each country. From the figure we see that Germany is the largest importer while Great Britain and France are the largest exporters due to the high capacity of respectively wind and nuclear power. The large electricity deficit in Germany is a result of high increase in demand. At 2030 levels Norway is an overall importer of energy in an average year.

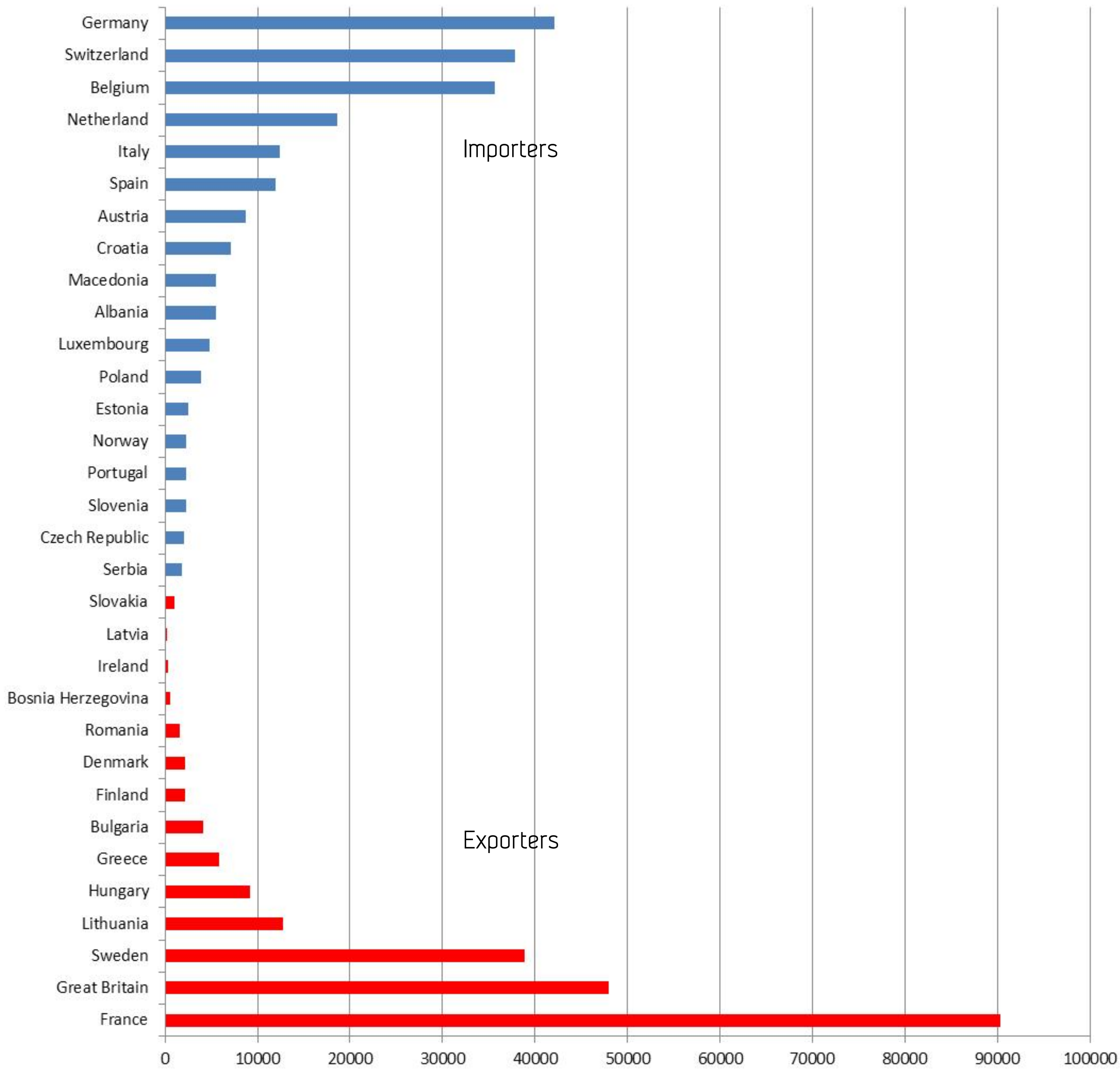

Figure 5-3 Electricity balance per country case "2030-1572" [GWh/year]

The annual transmission of electricity in the simulated system is illustrated in Figure 5-4. The figure shows net flow (difference between export and import), and only for those cases where net flow exceeds 5 TWh/year on average. The sum of arrows to/from a country will therefore not add up to the average net export for the country.

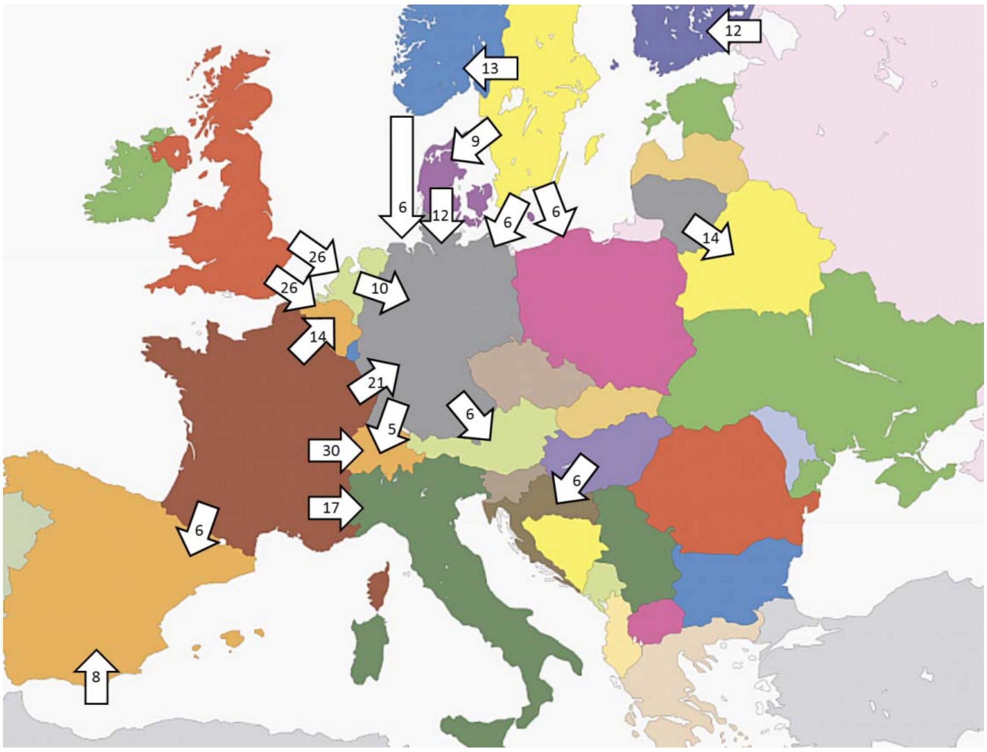

Figure 5-4 Electricity flow pattern, all connections with net exchange above 5 TWh/year are shown on the map

5.1.2 Development of electricity prices

The average yearly prices for electricity in Norway, Great Britain and Germany are shown in Figure 5-5. The general pattern when increasing the installed balancing power and transmission capacities is that prices will be more equal. This pattern can be observed both on the geographical and time scales. Figure 5-6 - Figure 5-9 show how the difference between peak prices and low prices is reduced from case "2030-1572" to "2030-10000".

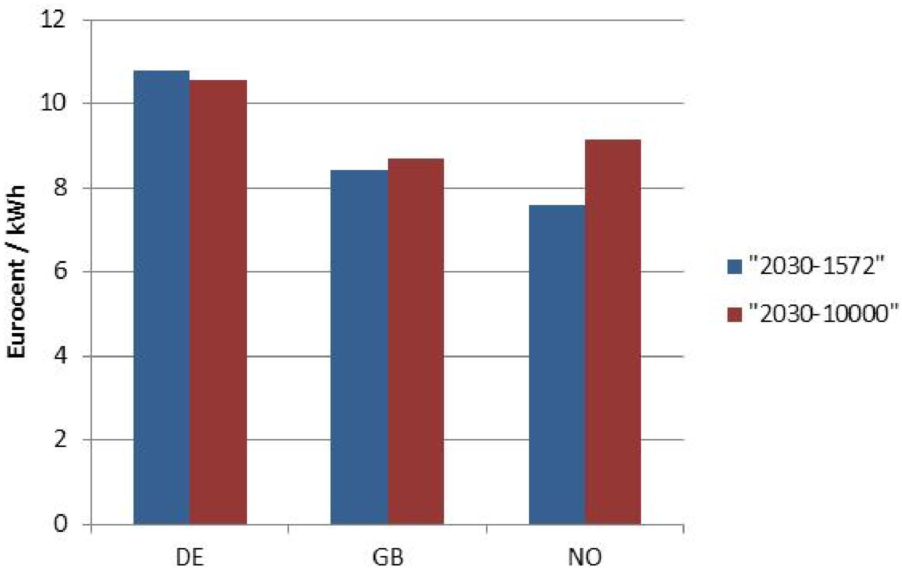

Figure 5-5 Average prices in selected countries for case "2030-1572" and "2030-10000"

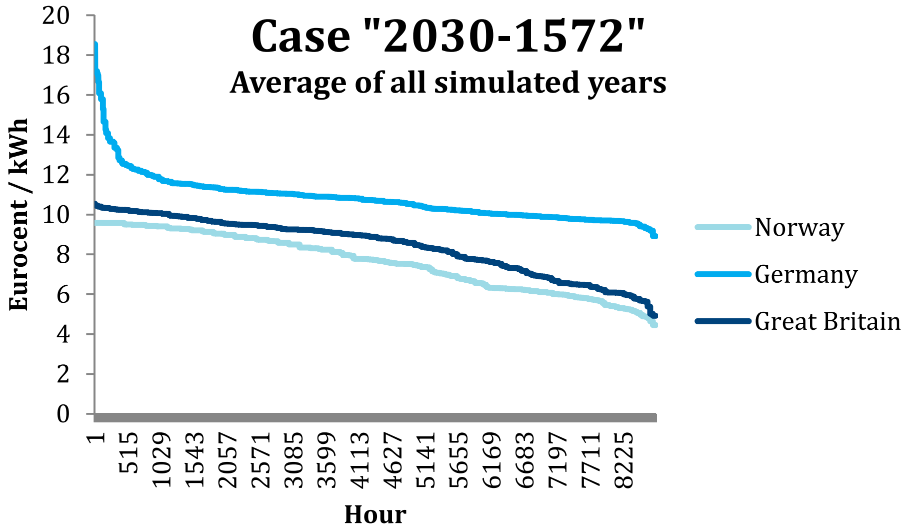

Figure 5-6 Duration curve of average prices for selected areas, case "2030-1572"

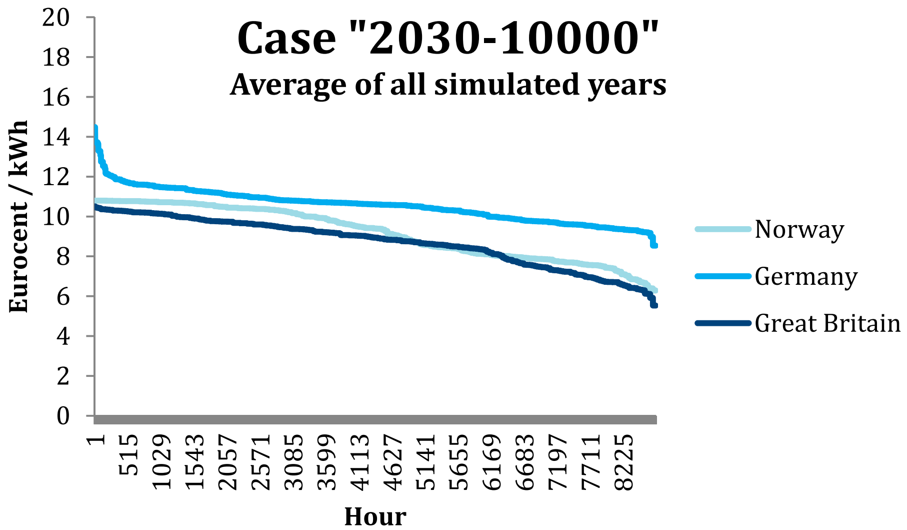

Figure 5-7 Duration curve of average prices for selected areas, case "2030-10000"

By comparing the price curve for Germany in Figure 5-6 and Figure 5-7 we see that the very high prices Germany has some hours during the year is reduced by installing increased capacity in the Norwegian hydro power system and by increasing the exchange capacity between Norway and Germany, Great Britain and the Netherlands. The phenomenon is also visible by comparing Figure 5-8 and Figure 5-9 which are showing the duration curve for the prices in Germany for a specific year. From Figure 5-8 it can be seen that Germany is reaching the rationing price (37.5 Eurocent/kWh) some hours the specific year.

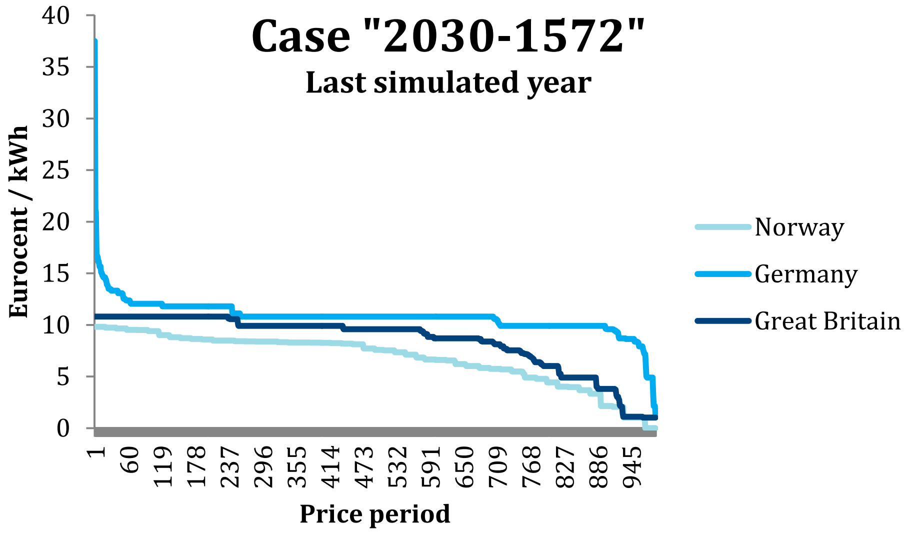

Figure 5-8 Duration curve of prices for a specific year for selected areas, case "2030-1572"

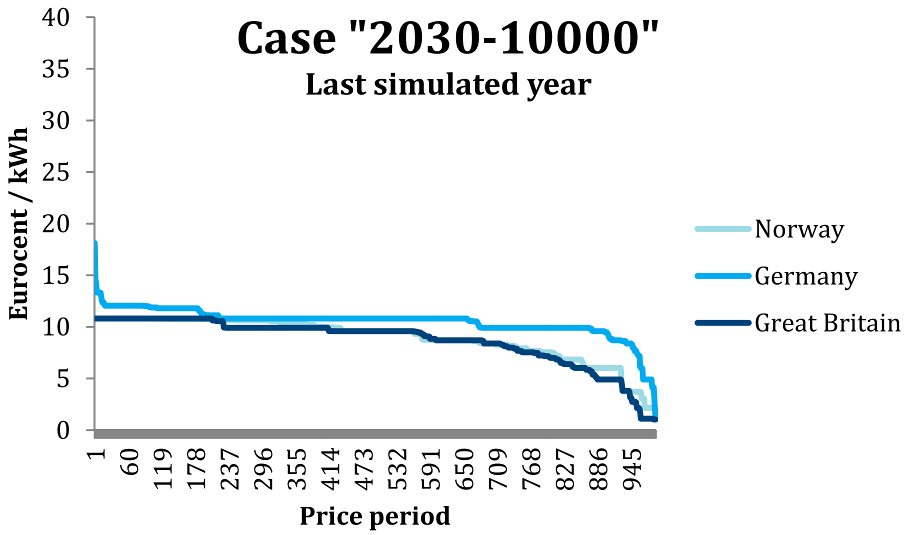

Figure 5-9 Duration curve of prices for a specific year for selected areas, case "2030-10000"

5.1.3 Transmission

The transmission analysis presented here is limited to the cables between Norway and Great Britain and between Norway and Germany. As seen in Figure 5-10 the cable between Norway and Great Britain is mainly used for exchange of balancing power. The direction of flow is largely dependent on the actual wind power production simulated and can thus be congested in both directions most parts of the year.

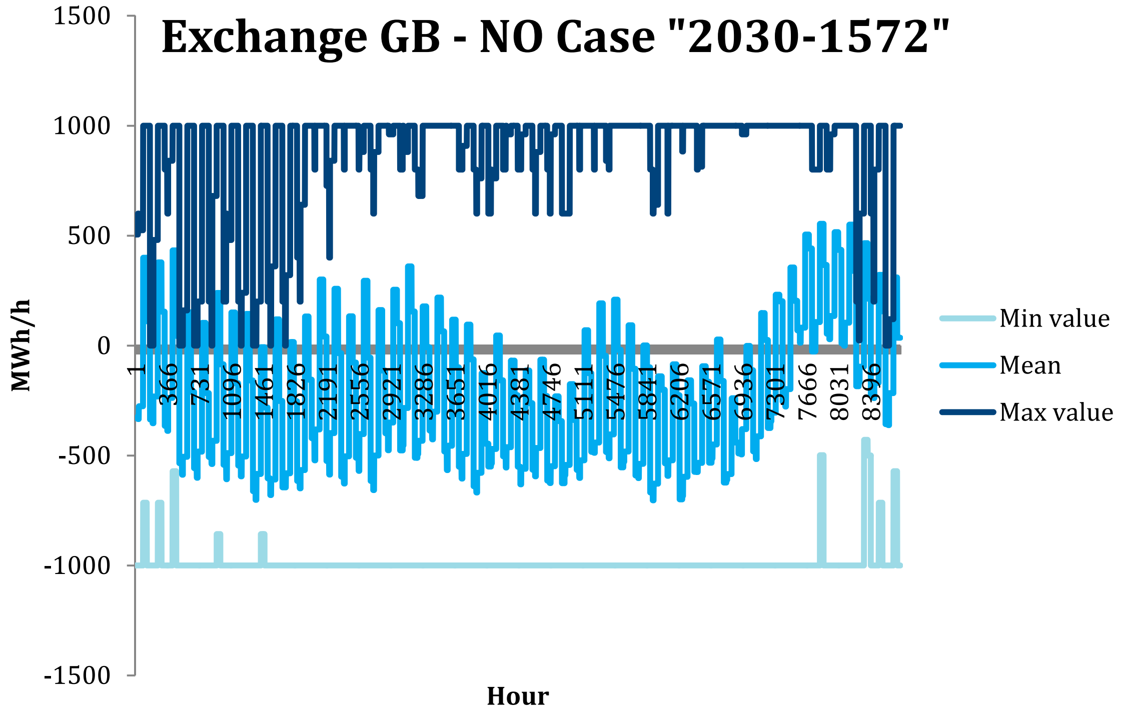

Figure 5-10 Transmission from GB to NO for case "2030-1572" [MWh/h]

A different pattern can be observed for the cable between Norway and Germany in Figure 5-11. In this case the flow is from Norway to Germany most of the time. As Norway is a net importer of electricity, a large net share of this flow goes from Sweden through Norway, as seen in Figure 5-4 as well.

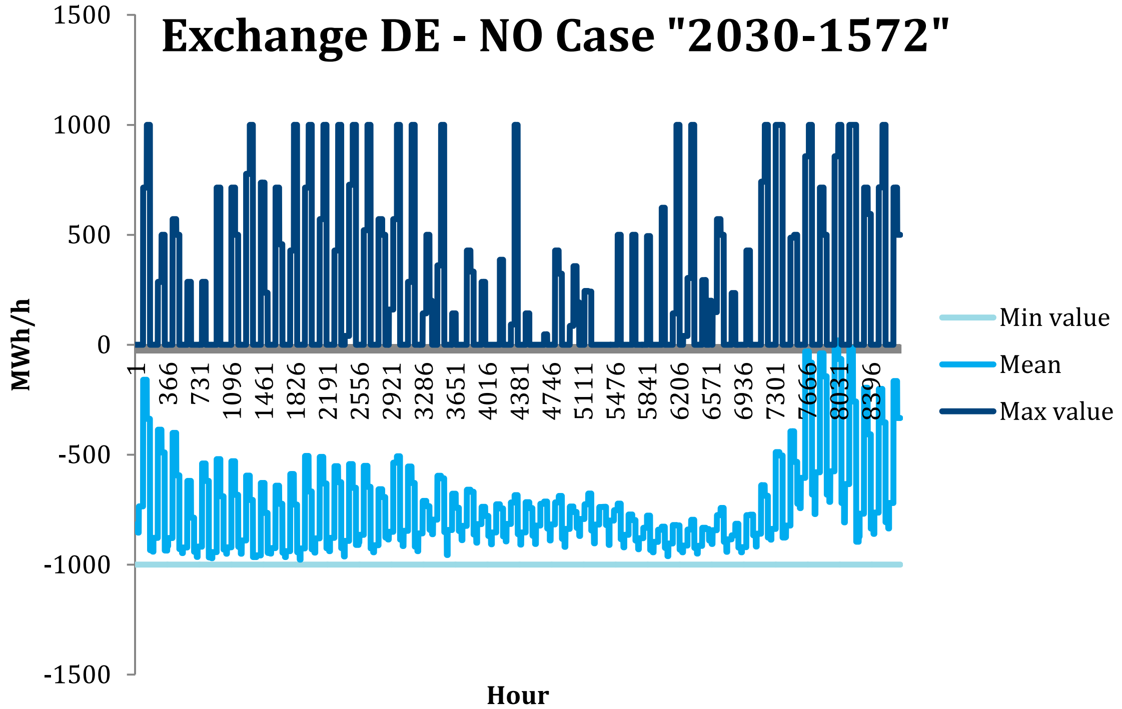

Figure 5-11 Transmission from DE to NO for case "2030-1572" [MWh/h]

In case "2030-10000" the flow between Norway and Great Britain follows a seasonal pattern. As there is more wind energy available in the winter, the flow goes to pumps in Norway in this period. When there is less wind in the summer, the stored energy is released and transferred back to Great Britain, as seen in Figure 5-12. This pattern corresponds to the observed utilization of Norwegian pumping units in Figure 5-14.

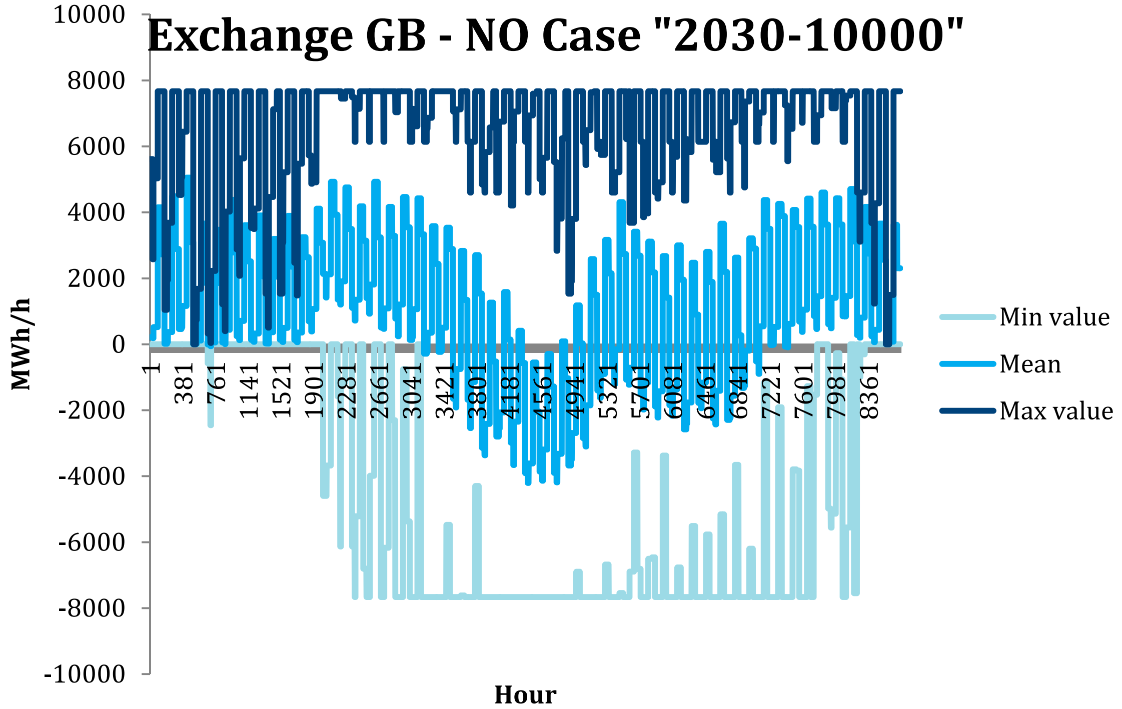

Figure 5-12 Transmission from GB to NO for case "2030-10000" [MWh/h]

Figure 5-13 resembles Figure 5-11, but even for Germany, a major importer of energy, there is excess energy in the winter available for pumping in Norway.

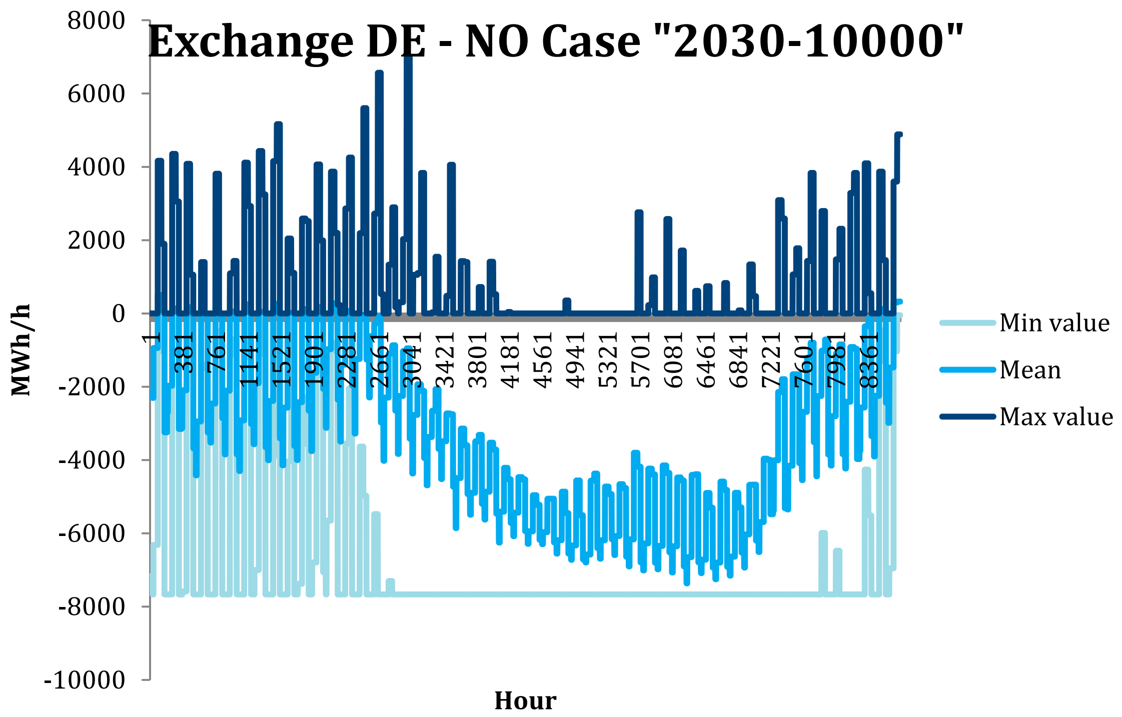

Figure 5-13 Transmission from DE to NO for case "2030-10000" [MWh/h]

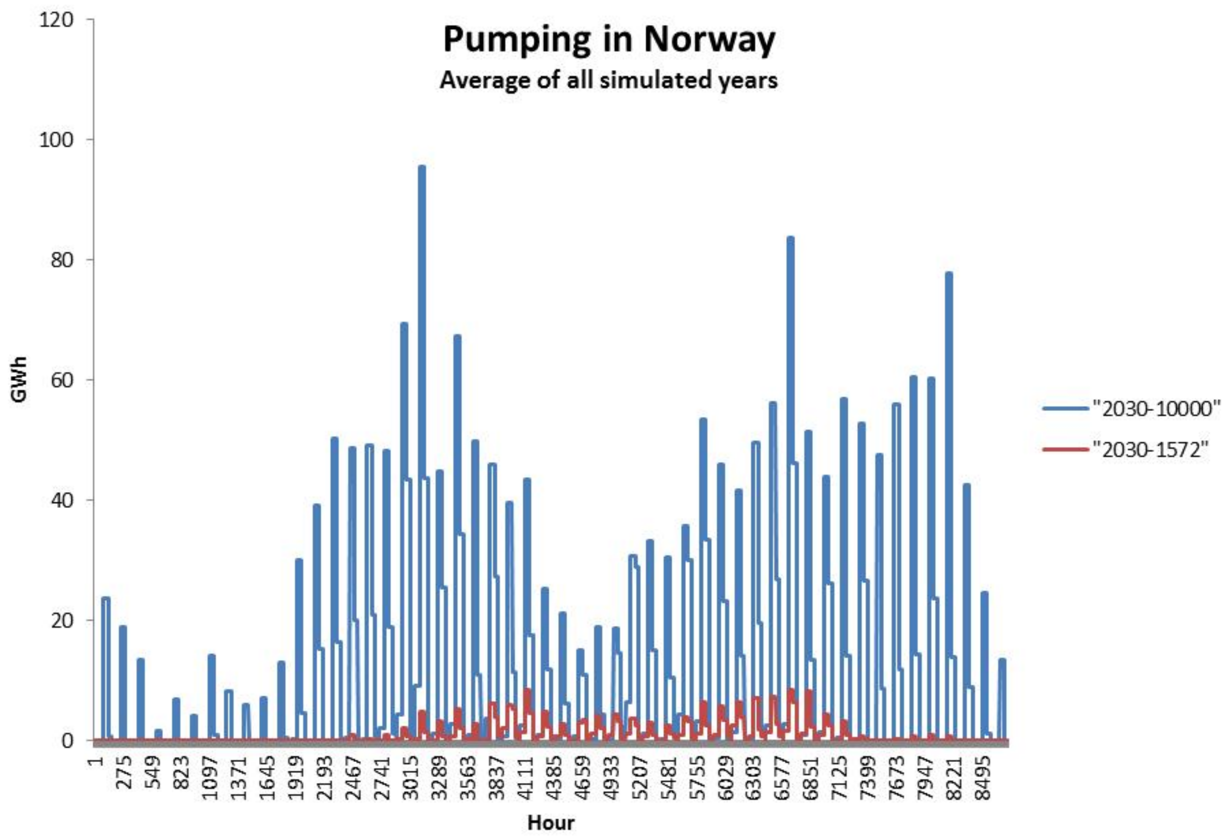

Figure 5-14 Pumping in Norway for case "2030-1572" and "2030-10000"

5.2 Cases "2050-1572" and "2050-10000"

5.2.1 Energy balances and emissions

The main results from the simulations of stage 2050 are shown in Table 5.2. With an even larger share of intermittent renewable energy sources than in 2030, the system impact also increases. Now the overall reduction in CO_2 emissions is 26 Mtons per year. This equals 3.5% of the total CO_2 emissions from electricity generation in Europe in Blue in 2050.

Table 5.2 Summarized results for case "2050-1572" and "2050-10000"

		"2050-1572"	"2050-10000"	"2050-10000"-"2050-1572"
CO2 emissions	[Mtons/year]	753	727	-26
Curtailment	[GWh/year]	6 826	4 221	-2 605
Dumping	[GWh/year]	131 142	111 960	-19 181
Lignite prod	[GWh/year]	41 963	40 763	-1 200
Coal prod	[GWh/year]	505 864	494 100	-11 764
Gas prod	[GWh/year]	636 769	598 715	-38 054

The reduction in fossil fuel generation is replaced by the system as shown in Figure 5-15.

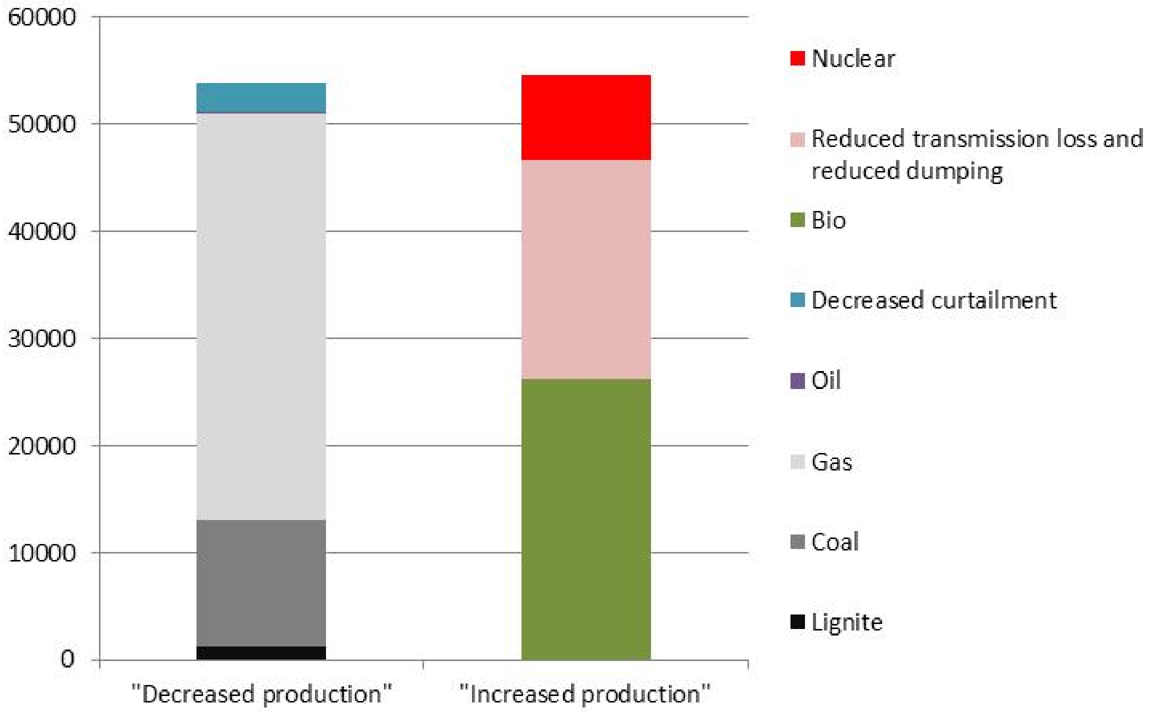

Figure 5-15 Main changes in electricity balance from case "2050-1572" to "2050-10000" [GWh/year]

An overview of the shares of different technologies per country is found in Figure 5-16. When compared to Figure 5-2 one sees that most countries have increased their installed wind power capacity with between 50% and 300%. We also see that Germany has a weaker power balance due to the decommissioning of all nuclear units.

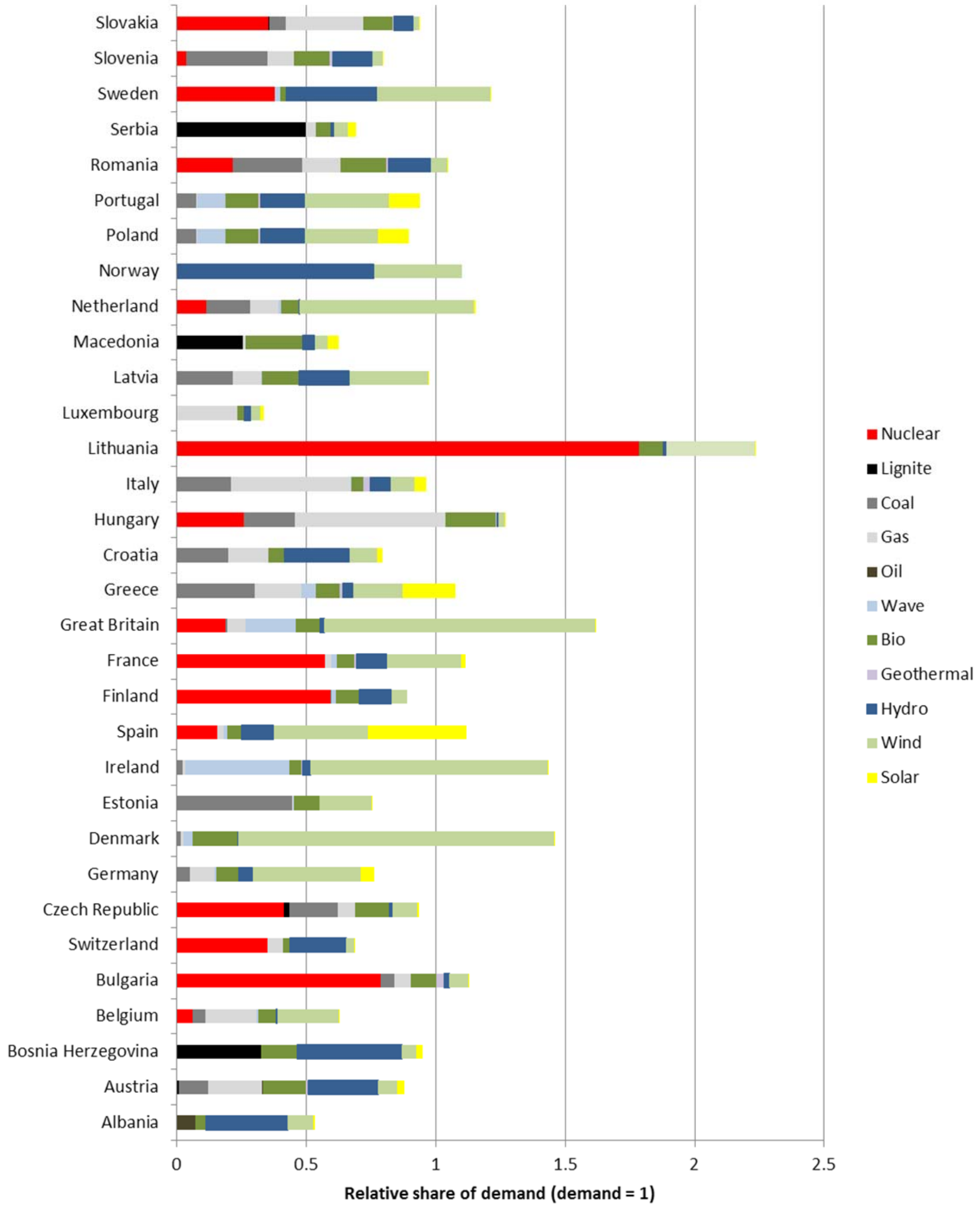

Figure 5-16 Electricity production per source in share of demand per country for case "2050-1572"

Figure 5-17 shows that the power balance differences between each country have been greatly magnified since 2030. Germany now imports above 200 TWh to cover its demand. Great Britain on the other hand has become the biggest exporter with an average export of 240 TWh/year. Norway has changed its position from a net importer to a net exporter due to the large new wind power capacity.

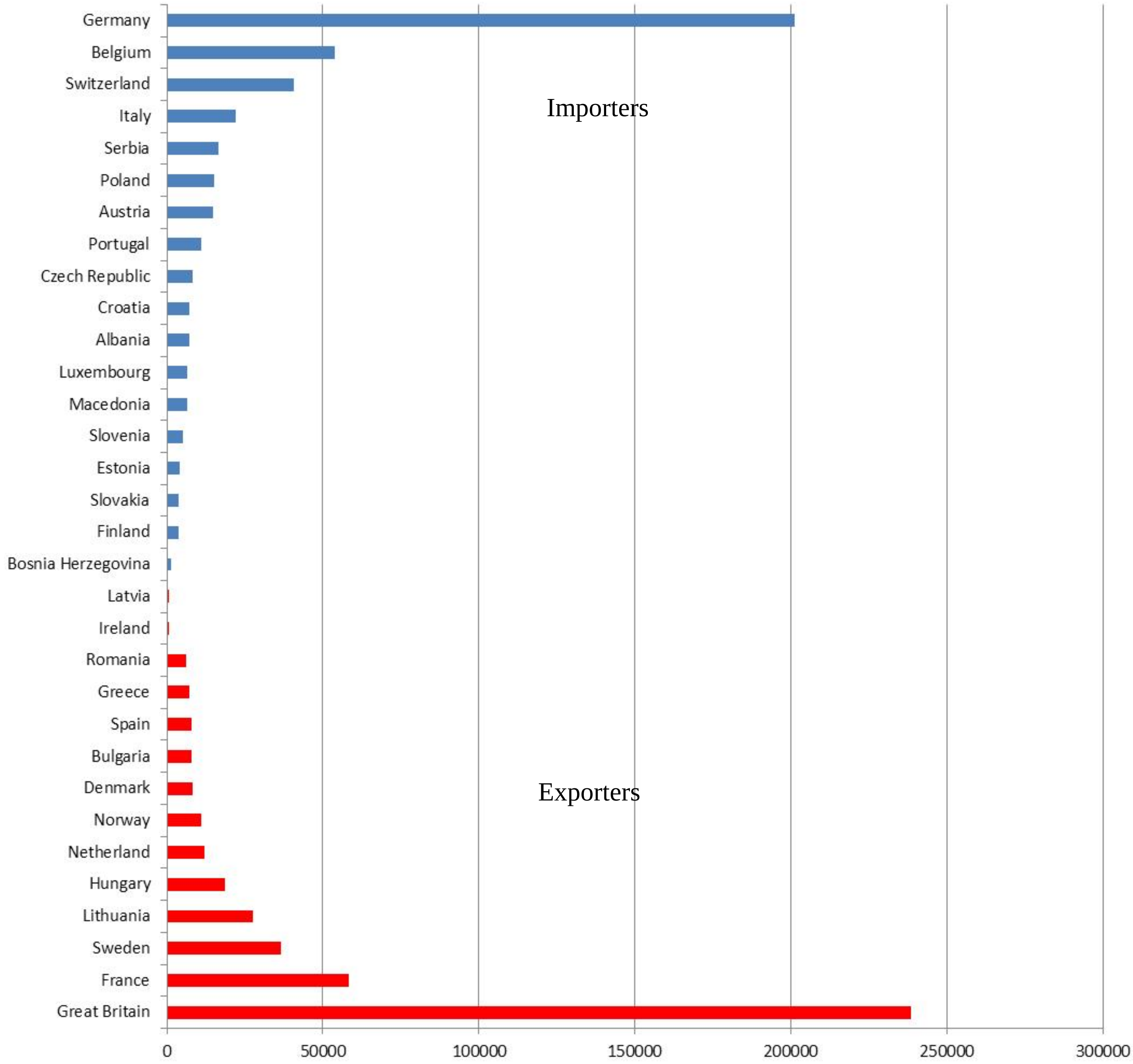

Figure 5-17 Electricity balance per country case "2050-1572" [GWh/year]

5.2.2 Prices

When studying the effects of increased balancing power, we observe the same harmonization of prices as seen from case "2030-1572" to "2030-10000". Figure 5-18 shows how average prices in both Norway, a net exporter of energy, and Germany, a net importer of energy, are drawn closer to each other. The same effect is seen in the average price duration curves in Figure 5-19 and Figure 5-20. From the duration curves in Figure 5-21 and Figure 5-22 of the last simulated year we see that there are cases where the price in Germany reaches the value of lost load at 37.5 Eurocent / kWh. This means there will be some rationing in the area. Without the nuclear power there is a simulated rationing in Germany in case "2050-1572" of 4 TWh and in case "2050-10000" of 1.6 TWh.

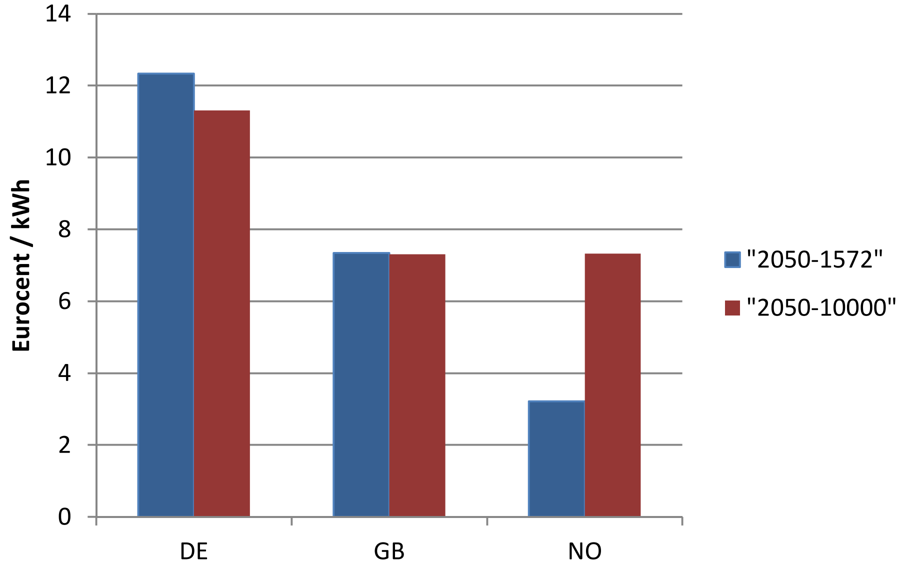

Figure 5-18 Average prices in selected countries for case "2050-1572" and "2050-10000"

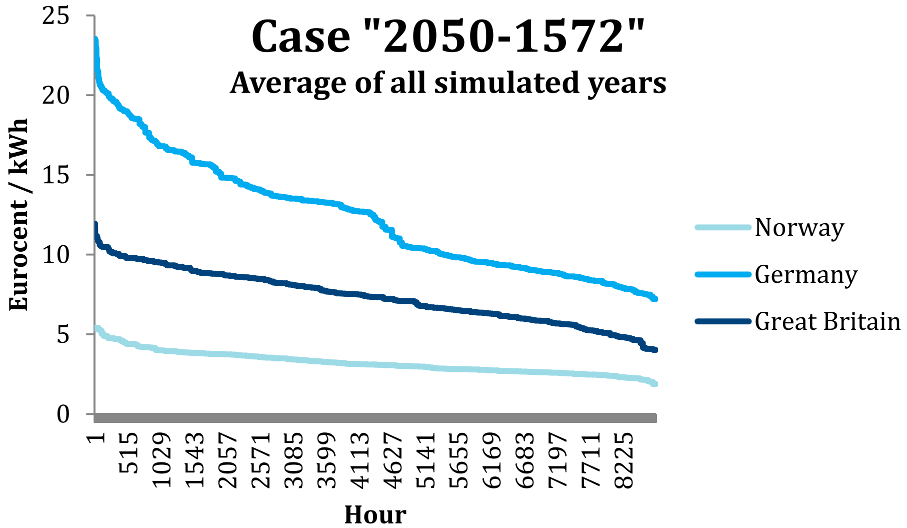

Figure 5-19 Duration curve of average prices for selected areas, case "2050-1572"

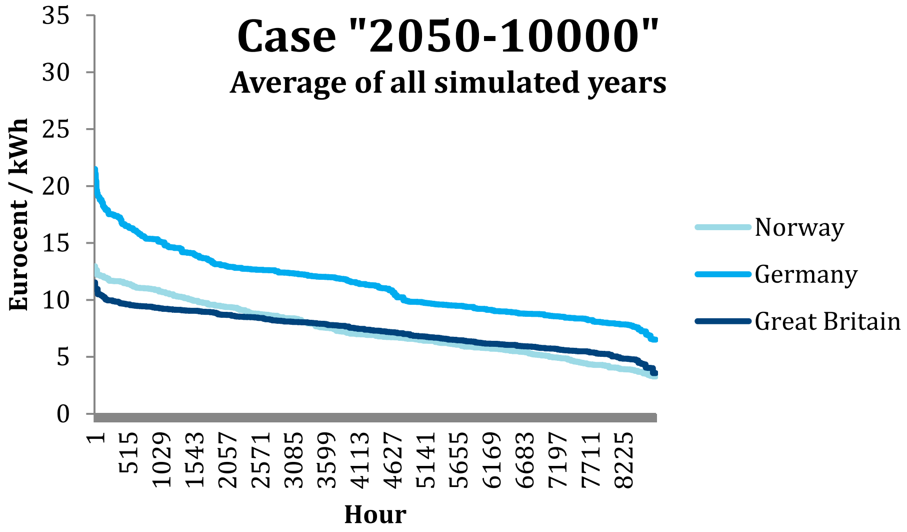

Figure 5-20 Duration curve of average prices for selected areas, case "2050-10000"

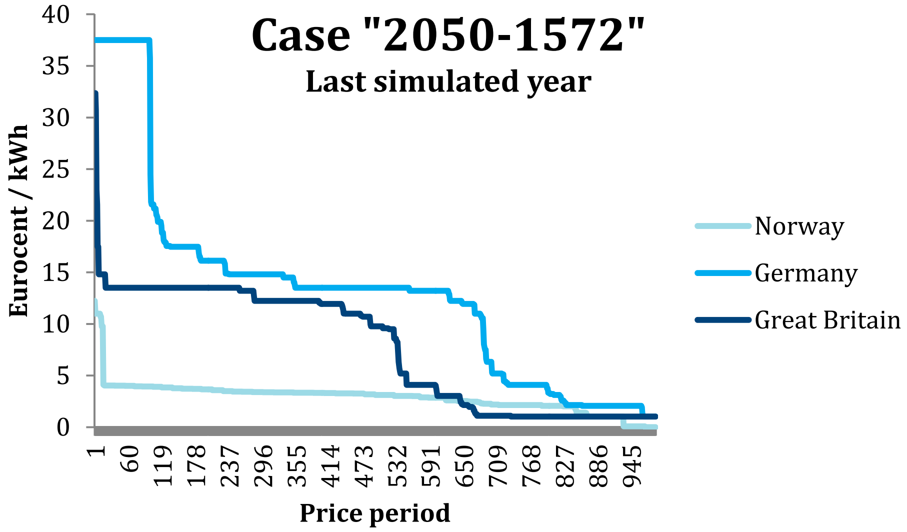

Figure 5-21 Duration curve of prices for a specific year for selected areas, case "2050-1572"

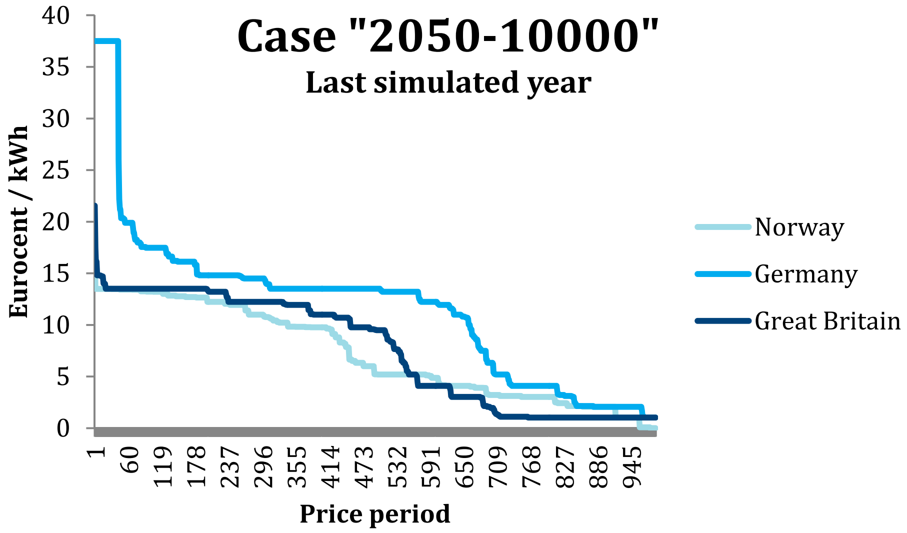

Figure 5-22 Duration curve of prices for a specific year for selected areas, case "2050-10000"

5.2.3 Transmission

The tendencies described in chapter 5.1.3 are even more evident in cases "2050-1572" and "2050-10000". With increased wind capacity in Great Britain there are congestions in all price periods in all parts of the year on the cable to Norway, as seen in Figure 5-23.

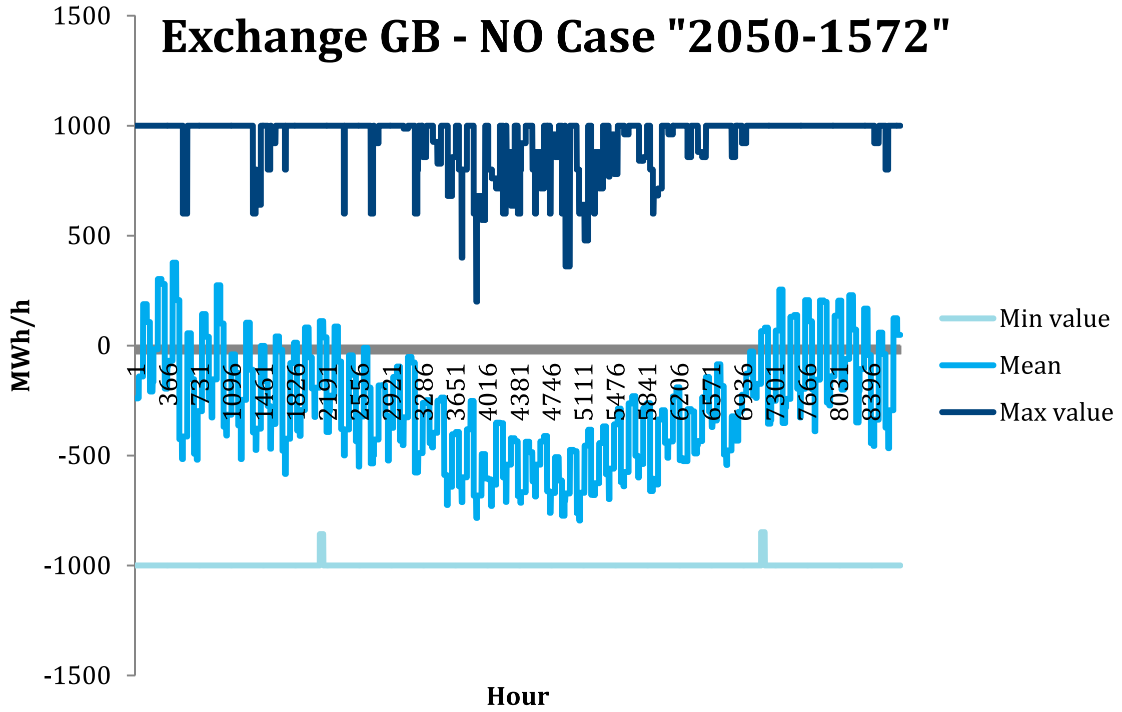

Figure 5-23 Transmission from GB to NO case "2050-1572" [MWh/h]

Although Germany now is an even larger importer of energy, there are more cases with enough wind in Germany to generate flow to Norway. As the green line in Figure 5-24 is not continuously reaching the max capacity, we understand that this happens only from time to time when there is surplus in the German production.

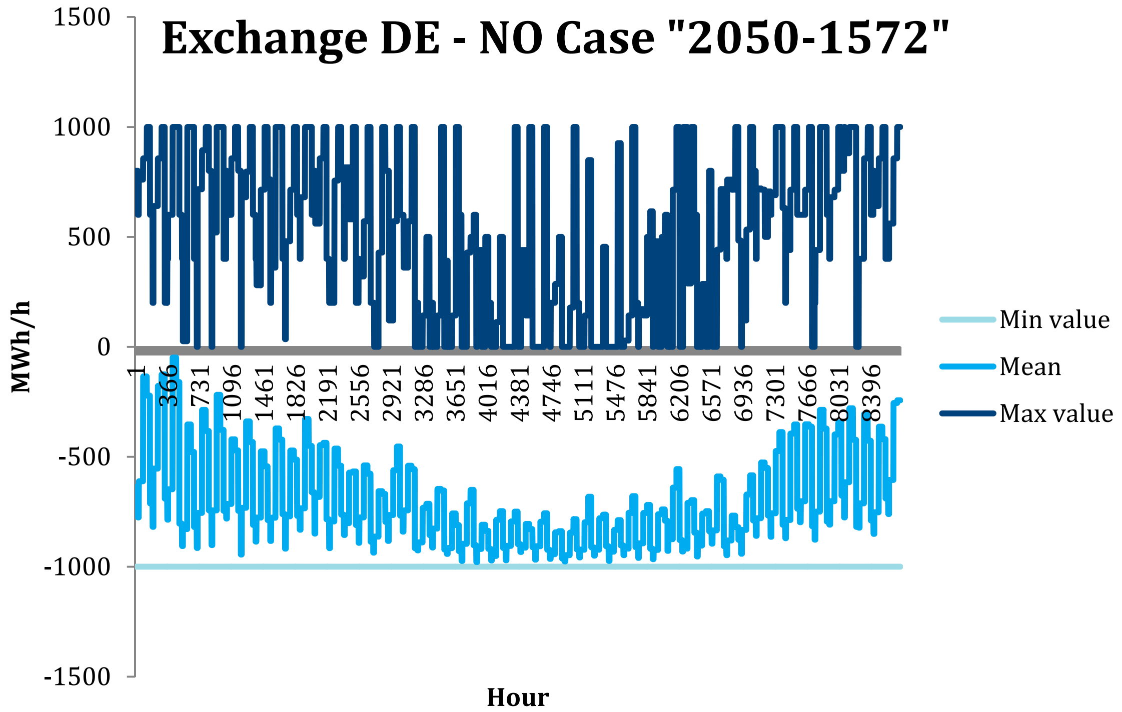

Figure 5-24 Transmission from DE to NO case "2050-1572" [MWh/h]

Figure 5-25 gives the clearest picture of the capability of Norwegian balancing power to be more than a short-term energy storage. Combined with Figure 5-27 we see how the transmission and pumping varies both within one week and over the year. As before we see that the excess wind in the winter season is stored and released in summer time.

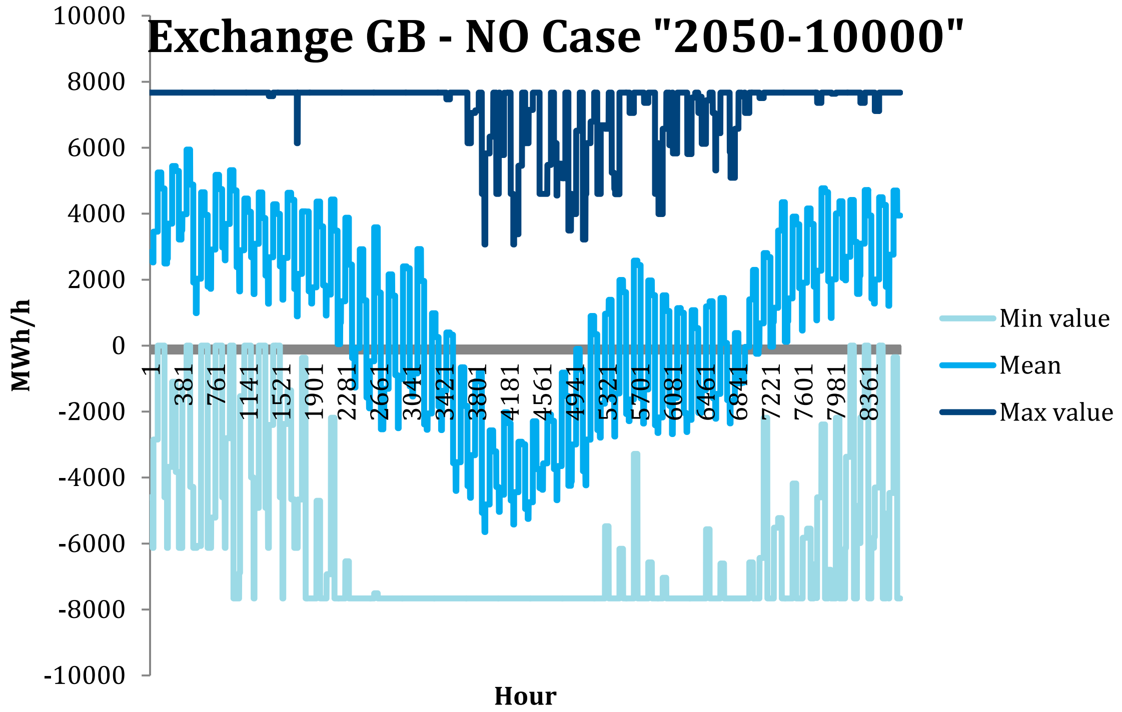

Figure 5-25 Transmission from GB to NO case "2050-10000" [MWh/h]

The pattern in Figure 5-26 is the same as in Figure 5-24. However, the capacities are now much larger. The large amount of congestion we observe from the transmission analysis shows that there is likely to be a further amplification of the impacts observed with an even larger amount of balancing power in Norway.

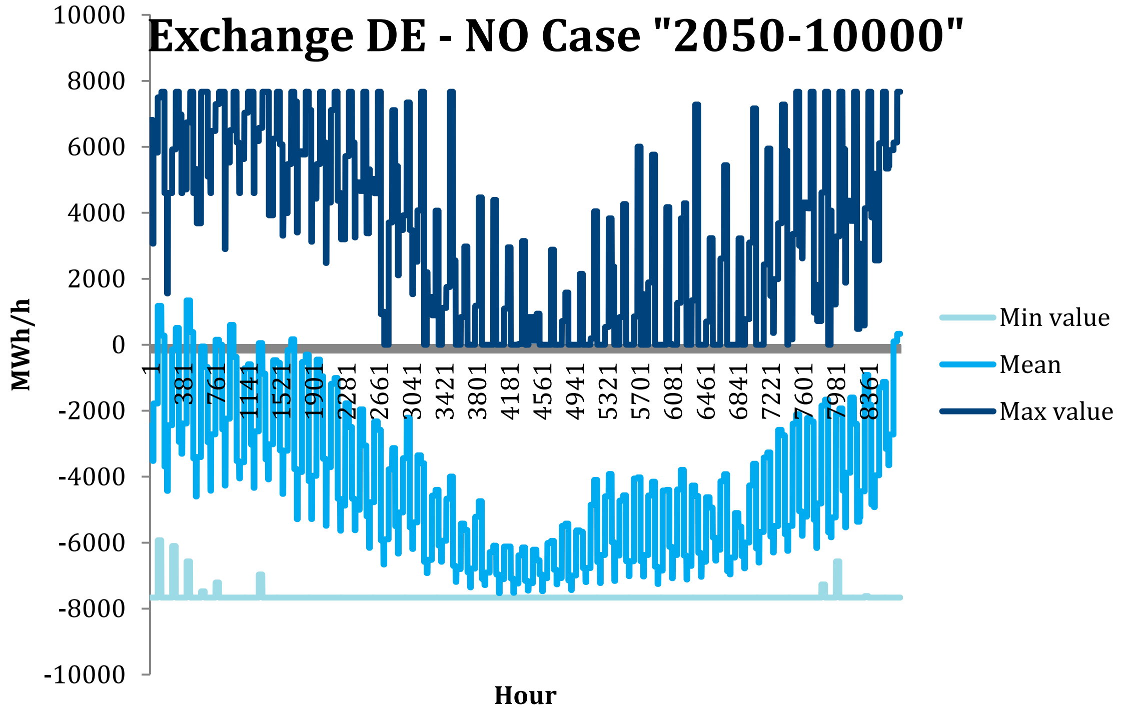

Figure 5-26 Transmission from DE to NO case "2050-10000" [MWh/h]

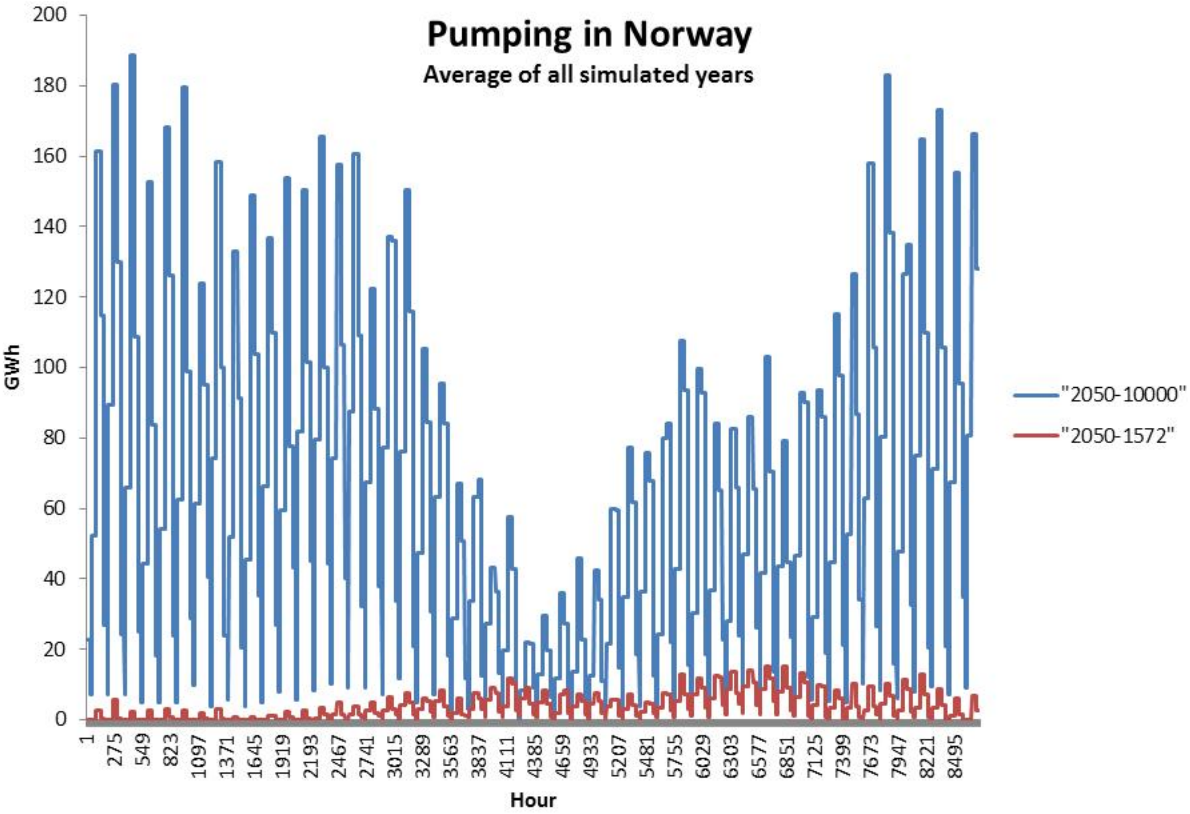

Figure 5-27 Pumping in Norway for case "2050-1572" and "2050-10000"

6 Discussion of results and conclusion

In this CEDREN project, the EMPS model is used for analyses of Norway as a "green battery" for Europe. The hydro power system in Norway is used for storing energy from periods with high production from intermittent resources like wind and solar to periods with low production from the same sources.

The analyses are performed on a European power system in 2030 and 2050. They are based on the Blue scenario from the SUSPLAN and the ZEB projects. The Blue scenario has very high volumes of renewable production as shown in Figure 3-5 and the electricity consumption has increased considerably compared to 2010, see Figure 3-4.

Four cases are analysed based on the Blue scenario:

- "2030-1572": the analyses are based on the Blue data for 2030 and a pumping capacity in Norway of 1572 MW. Transmission capacities are shown in Table 3.1.
- "2030-10000": the analyses are based on the Blue data for 2030. In addition the capacity of the Norwegian power system is increased with 10 000 MW in conventional turbines to in total about 40000 MW, but the total production is kept on the same level as for the 2030-1572 scenario. Further, the pumping capacity is increased with 10 000 MW to a total of 11572 MW. The transmission capacity between Norway and Great Britain, Germany and the Netherlands are increased with 20 000 MW
- "2050-1572": the analyses are based on the Blue data for 2050 and a pumping capacity in Norway of 1572 MW. Transmission capacities are shown in Table 3.1
- "2050-10000": the analyses are based on the Blue data for 2050. In addition the capacity of the Norwegian power system is increased with 10 000 MW to a total of about 40 000 MW, but the total production is kept on the same level as for the 2050-1572 scenario. Further, the pumping capacity is increased with 10 000 MW to a total of 11572 MW. The transmission capacity between Norway and Great Britain, Germany and the Netherlands is increased with 20 000 MW.

6.1 Observed results from the analyses

Before the analyses it was expected that introduction of increased capacity in the Norwegian hydro power system and increased transmission capacities between Norway and neighbouring countries would lead to changing in pumping patterns in Norway, reduction of rationing, reduction of surplus, reduction of CO_2 emission and changes of electricity prices in Europe. Below each of these aspects are discussed in more detail.

Pumping

As expected, the pumping is increasing when the pump capacity is increased, see Figure 5-14 and Figure 5-27. Further, the pumping is increasing with increasing shares of intermittent production in the system. The dark blue curves in Figure 5-14 and Figure 5-27 show that it is pumped much more frequently and with higher volumes (GWh) in 2050 than in 2030. However, with the installed pump capacity of 11572 MW in the case "2050-10000" and the high share of intermittent production, the volume of pumping was expected to be higher. More detailed studies shows that only water equivalent to 11.4 TWh of net energy were pumped in the Norwegian system. This is explained further in section 6.2.

Reduction of rationing

In a system with very high shares of production from wind and solar resources like the German system in Blue in 2050, there may not be possible to cover all demand to an acceptable price in periods. Without backup resources, rationing may be necessary when it is limited wind or radiation. If Norwegian hydro power is used as a "battery", the Norwegian hydro power system is expected to cover parts of the German demand and to reduce the probability for rationing in these periods.

The rationing price is in the analyses exogenous set to 37.5 eurocent/kWh, i.e. if the prices reaches 37.5 eurocent/kWh there will be rationing in the system. Detailed studies of the results show that there is about 4.2 TWh rationing in the German system in "2050-1572". In "2050-10000" the rationing is reduced to 1.7 TWh. Also the price curves in Figure 5-21 and Figure 5-22 show that there is a rationing price in Germany some hours a year, and that the number of hours with rationing is reduced from case "2050-1572" to case "2050-10000", i.e. the rationing in these analyses is not completely removed from the German system. This is further discussed in chapter 6.2.

Reduction of surplus

Use of Norwegian hydro power as a "battery" is expected to reduce the surplus in the production system in Europe. Surplus is in this context energy produced from wind turbines or solar systems in a period where it is not sufficient demand to utilise the produced energy.

Detailed studies of the results show that in the case "2050-1572" there is a surplus of offshore wind production in Great Britain of 53.4 TWh per year. In the case "2050-10000" the surplus is reduced to 45.3 TWh. The surplus is reduced, but still a lot of energy has to be dumped.

Germany has a small surplus in "2050-1572" (1.3 TWh). In "2050-10000" it is reduced, but not completely.

Reduction of CO_2 emission

The CO_2 emissions are reduced with 26.3 Mtons/year from case "2050-1572" to "2050-10000", see Table 5.2. The main changes are in the Netherlands (9.5 Mtons/y), Germany (6.9 Mtons/y) and in Great Britain (4.1 Mtons/y). However, in 2050 there are still 734 MTons/y CO_2 emissions in Europe.

The fossil production in Germany is reduced with approximately 11.5 TWh/y, but still there is about 100 TWh coal and gas production left in "2050-10000".

Impacts on the electricity prices

The development of average marginal prices is shown in Figure 5-5 and Figure 5-18. As shown in the figures the spot price is decreased in Norway from 2030 to 2050, even though the demand is increasing with about 17 TWh in the same period. The reason for the decrease is that a lot of new renewable energy is integrated into the system.

When the transmission capacities between countries are increased, the prices in the involved countries will be more equal. As shown in the figures, this happens both from "2030-1572" to "2030-10000" and from "2050-1572" to "2050-10000". The prices in Germany decrease and the prices in Norway increase.

6.2 Improvements and suggestions for further work

Use of Norwegian hydro power as a "green battery" for Europe is analysed and compared for the cases "2030-1572" and "2030-10000" and for the cases "2050-1572" and "2050-10000". For both 2030 and 2050, the capacity in the Norwegian power system as well as the pumping capacity is increased from the 1572 case to the 10000 case. In addition the exchange capacity between Norway and Great Britain, Germany and the Netherlands are increased with a total of 20000 MW. I.e. there are made two major changes at the same time, and the reduction in the surplus, the rationing and the CO_2 emissions are results of both changes.

The design of the cases for analysis

It is of course necessary to increase transmission capacity from Norway to other countries to use the increased power and pumping capacity in the Norwegian system for balancing purposes in other countries. A considerable part of the observed changes is a result of increased transmission capacity, and has less to do with the increased capacity in the Norwegian hydro power system. The transmission capacity from Great Britain to Germany is increased (going through Norway) and also the transmission capacity from Sweden to Germany. Through the increased capacities, Great Britain and Sweden are exporting cheap renewable energy to Germany, and the effects would have been the same with increased capacities directly from Great Britain to Germany and from Sweden to Germany. In further analysis the 1572-cases should be run with the high level of transmission capacities, and the only change from the 1572 cases to the 10000 changes should be the increase of capacity in the Norwegian production system. Then, it will be possible to calculate more accurately the effects of Norway as a "green battery" for Europe.

The use of the EMPS model

In these analyses a one-node per country version of the EMPS model is used. Each node is modelled with one reservoir and one pump. The pumping functionality is implemented such that the hydro power plant is either pumping or producing. Thus, in the current model the Norwegian battery will only "charge" when the whole Norwegian load is supplied and there is still surplus of energy which could be used for pumping. The model simplification explains the limited level of pumping.

Further analysis should be run on the EMPS version with several nodes per country. Still countries like Switzerland and Austria could be run with a simplified model (e.g. two or a few nodes per country), but Norway should be run with a more detailed representation of the hydro power system. Such analysis will probably show more pumping in Norway.

Further, it is not used start/stop costs for thermal production due to substantially increase in the run time for the models. As a result the thermal production will to some degree be used for balancing intermittent renewable production instead of Norwegian hydro power. Use of start/stop costs for thermal production (which is a more realistic approach) would probably have increased the use of Norway as pump-storage for Europe.

It is also worth mentioning that thermal production is often run as standby production which also generates emissions. If Norwegian hydro power is working as a battery for Europe, the standby production could be reduced. Use of thermal production as standby has not been included in these analyses.

The implementation of the EMPS model

The EMPS model is historically implemented and used for power systems with mainly seasonal storage of water. As a consequence the algorithm will check the reservoir levels against the mathematical restrictions only once a week which is too seldom for a system used as a short term battery for balancing purposes. A detailed study of the results shows that the pumping is at a similar level in France and in Spain as in Norway, even though France and Spain have much more limited reservoir capacities.

To be able to perform high quality analyses of future RES dominated power systems, the EMPS model should be improved with more frequent check of the reservoir levels.

Other aspects

In further analysis at least the following could be studied in sensitivity analyses:

- The results of the changes in CO_2 emissions in a future situation where Norway is used as a "green battery" for other countries compared to a situation where it is not, depends very much on the production portfolio in the rest of Europe and especially in Germany. The relationship between lignite, coal and gas will be crucial for changes in CO_2 emissions. Analyses should be performed with different future production portfolios. In the ZEB project CO_2 emissions for five different scenarios (including the Blue) are analysed. Those scenarios may be considered for further investigation [Graabak, 2011].
- The results will also depend on the assumed prices of CO_2 allowances. The effect of different CO_2 allowance price scenarios could be studied in future analyses.

A final conclusion is that this work must be regarded as a preliminary of analysis the impacts of Norwegian hydro power as a "green battery" for Europe. The work has given increased insight in necessary improvements in design of the cases for analysis, the use of the EMPS as well as the implementation of the model before it is possible to finally quantify the impacts of Norwegian hydro power working as a "green battery" for Europe.

SINTEF

7 References

[Auer, 2008]	Auer et al: "Guiding Large-Scale and Least-Cost Grid and Market Integration of RES-Electricity in Europe", 2008, *www.greennet-europe.org*.
[Capros, 2005]	Capros et al: "The Primes Energy System Model – Summary Description", National Technical University of Athens (NTUA), Athens, Greece, 2005, *www.e3mlab.ntua.gr*.
[ENTSO-E, 2012]	www.entsoe.eu
[Eurelectric, 2009]	Statistics and prospects for the European Electricity Sector 37th Edition Eurprog 2009. Eurelectric, october 2009.
[Faber, 2007]	Faber et al: "The model Green-X", Vienna University of Technology - Energy Economics Group (EEG), Vienna, Austria, 2007, ***www.green-x.at*.**
[Graabak, 2011]	Graabak I., Feilberg N.: "CO_2 emissions in different scenarios of electricity generation in Europe", TR A7058, January 2011
[IEA, 2009a]	"World Energy Outlook 2009", International Energy Agency (IEA), 2009, ***www.iea.org*.**
[Miljøstatus, 2012]	www.miljostatus.no
[RES2020]	www.res2020.eu, accessed in January 2012
[SUSPLAN, D1.2]	"SUSPLAN", Deliverable D1.2: "Scenario Guidebook: Definition of a Consistent Scenario Framework", Seventh Framework Programme project nr. 218960 (EU), www.susplan.eu, 14/12/2009.
[SUSPLAN, D7.2]	"SUSPLAN", Deliverable D7.2: "Final report" Seventh Framework Programme project nr. 218960 (EU), www.susplan.eu, 22/12/2012.
[Wolfgang, 2009]	"Hydro reservoir handling in Norway before and after deregulation" Ove Wolfgang et.al. Energy 34 (2009) 1642–1651

.

SINTEF

Technology for a better society

www.sintef.no