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Report

The significance of international hydropower storage for the energy transition

Contracting entity
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Commission
Prognos advises decision makers in business and politics throughout Europe. Based on neutral analyses and underpinned forecasts, practice-orientated decisions and future strategies for companies, public authorities and international organisations are developed.

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1 Summary

(1) Prognos AG was commissioned by the World Energy Council – Germany at the end of April 2012 to compile a **study on the significance of international hydropower storage for the energy transition**. The question at issue is whether and to what extent international hydro-storage plants are able to store surplus electricity from renewable energy sources and to release backup electricity. We expect that Germany will not be able to simultaneously consume 38 terawatt hours (TWh) of electricity from renewable energy sources by the year 2050. The excess capacity can then reach up to 60 gigawatt (GW) within individual hours.

(2) **Germany,** due to its geological conditions, has mainly pumped-storage plants at its disposal. Hydro-storage and pumped-storage installations together have a capacity of 6.8 GW and a working volume of about 0.05 TWh. This capacity can be used for only about 6 to 8 hours in each case. More pumped-storage installations with a capacity of approx. 5 GW are planned or in the process of approval.

(3) **Scandinavia** (here: Norway and Sweden) today have a working volume of 116 TWh in hydropower storage installations, which is about 2,300 times larger than that in Germany. Also, the storage volume of the Alpine region (here: Austria and Switzerland) is at about 12 TWh not nearly as large as that in Scandinavia. The findings therefore focus on Scandinavia, because Norway and Sweden are capable to provide the largest storage capacities in the **long term**.

(4) In the **short and medium term**, however, the storage capacities of the **Alpine region,** in particular, can contribute to the integration of renewable energies, especially the photovoltaic systems in the south of Germany. However, the transmission capacities for the storage of electricity from the north German wind energy facilities towards the south are still lacking. Expansions are planned in the field of pumped-storage plants in Switzerland and Austria up to the year 2020, the grid infrastructure is largely in place there. In the long term, the possible use of these capacities by third parties depends on the development of renewable energy sources in the Alpine region.

(5) The most energy efficient type of storage is the so-called **indirect storage:** this means that electricity from German surpluses is consumed directly in Scandinavia, while the local hydroelectric storage capacities are spared. At a later stage, electricity can then be generated in the hydroelectric storage plants in Scandinavia for export purposes. An expansion of the Scandinavian hydro-storages for this purpose is not necessary for the time being.

(6) A prerequisite for indirect storage is the construction of **interconnectors** between the countries and the reinforcement of the land-based transmission network. The present study focuses on interconnectors. A land-based network expansion, without the construction of new interconnectors, is already partly planned in the considered countries and was not considered here. At present, the interconnectors to Scandinavia are still weakly dimensioned with about 3 GW (via Denmark). Up to now, a direct connection between Norway and Germany still does not exist. Reinforcements of the connections over Denmark to Scandinavia are currently under construction (Skagerrak 4). Furthermore, two subsea cable connections between Norway and Germany are in planning with the NORD.LINK and NorGer projects (planned implementation of the first interconnector: 2018)[1]. Interconnectors are not only capable to contribute to the balancing out of supply and demand, but also to provide a part of the system support services and thereby to increase the security of supply.

(7) The pending changes in the design of the electricity market and in the energy markets cause the analyses of the **economic efficiency** of new interconnectors to be fraught with great uncertainty. Price differences between Scandinavia and continental Europe are likely to gradually decline with the coupling of the electricity markets and will also dampen economic efficiency. In addition, interconnectors to Germany are under competitive pressure with every new connection to be built between Scandinavia and other countries such as the Netherlands or the UK.
The forecast by Prognos estimates the **economic potential** for the **construction of new interconnectors** between Germany and Scandinavia at **7 to 12 GW** from now up to 2050 - including the concrete projects already planned (see paragraph 6). Thereby, 10 to 20 TWh, or more exactly, 26 to 52% of the German electricity surplus can be utilised. In order to raise this potential, an open market design is needed that will allow power supply from abroad, as well as risk-participation by the state, depending on the circumstances.

(8) In the long run, the indirect storage of surplus electricity from renewable energy sources in the Scandinavian hydro-storage power plants can contribute significantly to the **supply security** and the **integration** of renewable energy sources, and hence to the energy transition in the process. In this regard, the hydroelectric installations in the Alpine region can already make a contribution in the short and medium term.

1 The sequence of construction of NORD.LINK and NorGer was not yet decided upon at the publication time of this study.

2 Background and assignment

(1) Prognos AG was commissioned by the World Energy Council – Germany at the end of April 2012 to compile an **expert report** on the **significance of international hydropower storage for the energy transition** in Germany. A year after the launch of the energy transition, implementation issues have been discussed intensively. In this context, it needed to be clarified to what extent hydropower storage installations abroad can contribute to absorb excess electricity from renewable energy sources and to make back-up electricity available.

(2) The **basic suitability of large storage facilities** to balance out electricity supply and demand is beyond doubt, also over longer periods of time. Thus, the panel of experts for environmental issues ("Sachverständigenrat für Umweltfragen") in 2011 also submitted a study entitled "Ways towards 100% electricity supply from renewable energy sources", in which the cooperation with Norway and Denmark played a central role. In this study it is shown that already by 2020 a transmission capacity to Norway of 16 GW and by 2050 a transmission capacity of 46 GW would be required to store electricity from the German production in Norwegian hydropower storage facilities at any point in time [SRU 2011, Scenario 2.1 a]. From today's perspective, however, the question is raised as to whether such an intensified transmission does make economic sense. In addition, another valid question can be added about its feasibility (at least until 2020) given the long planning and implementation timeframes required for interconnectors.

(3) In this context, the present expert report attempts to give a **realistic assessment** of the contribution of international hydroelectric storage capacities to the energy transition in Germany. In addition to Germany, countries such as Norway, Sweden, Switzerland and Austria formed part of the survey, because they have large hydroelectric storage facilities. Individually will be discussed:

- the **challenges** arising from the expansion of renewable energy sources along the target lines set by the German Federal Government,
- which potential **solutions** are available in addition to hydroelectric storage capacities,
- which **storage potentials** are available in the **countries** under discussion, namely Germany, Norway, Sweden, Switzerland and Austria, and
- how these potentials can be utilised in an **effective and economically viable** manner.

(4) To answer these questions, existing **documentation** was evaluated and own analyses of the economic possibilities of hydroelectric utilisation were conducted by applying the **power market model** of Prognos AG.

(5) In order to verify the assessments of the international aspects, we involved **partners** from each country in the discussion of the assumptions and premises, as well as the conclusions. These were:

- Norway: Statkraft AS, Statnett SF
- Sweden: Vattenfall AB, Svenska Kraftnät AB
- Switzerland: swisselectric
- Austria: Energie-Control Austria für die Regulierung der Elektrizitäts- und Erdgaswirtschaft (for the regulation of the electricity and gas industry), government controlled public institution ("E-Control")

For Germany:

- Vattenfall GmbH
- 50Hertz Transmission GmbH
- TenneT TSO GmbH
- RWE AG
- EnBW Energie Baden-Württemberg AG
- E.ON AG

as well as the representatives of the World Energy Council – Germany.

A total of 3 workshops took place with these partners during which the assumptions and conclusions were extensively tested on their viability. Having said that, Prognos AG accepts the sole responsibility for the resulting contents of this investigative study.

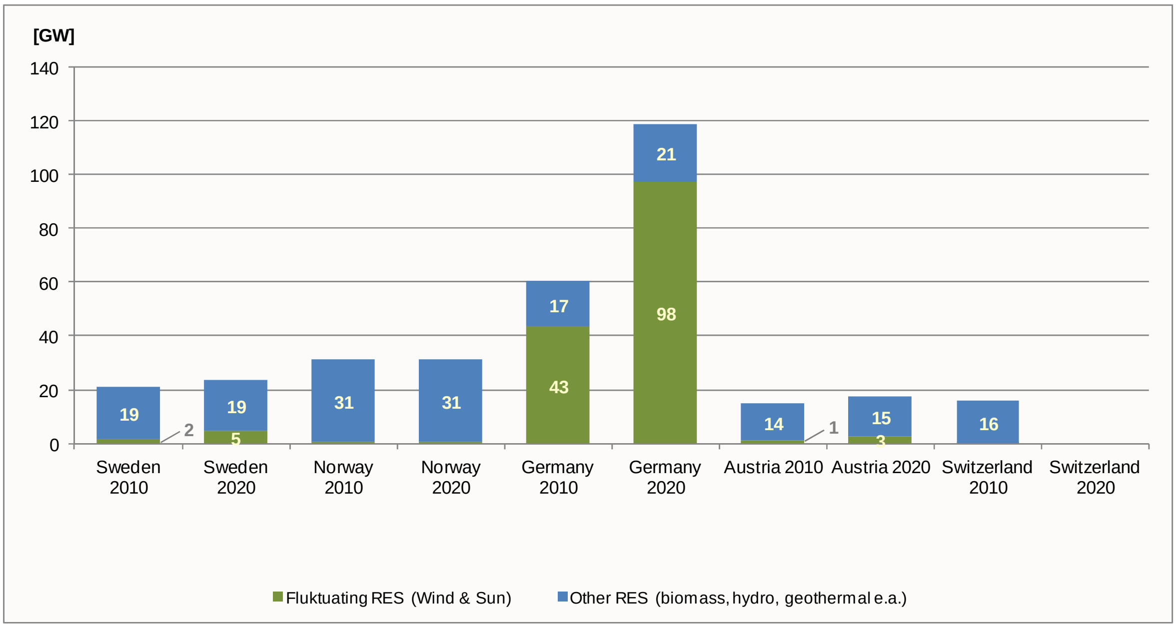
(6) The energy transition in Germany is a "project of the century". The present study aims to contribute **to the debate** on how to implement this transition, which is so important to Germany. Critical and/or constructive comments and contributions to this study are most welcome.

3 Challenges of the energy transition in Germany and potential solutions

(1) The German energy transition is observed with great interest internationally, by some with scepticism or concern, because of the impact on neighbouring European countries. Admittedly, there is consensus in the EU that in order to reduce CO_2 emissions, energy efficiency and the share of CO_2-free electricity generation need to be increased. To that extent, the German energy transition represents no solo effort. However, the simultaneous phasing-out of nuclear energy in Germany increases the demand for action compared to other countries. The fast growing components of fluctuating power generation and the challenges associated with it, in particular give rise to debate.

(2) Germany, however, is not the only country that pursues ambitious objectives in the development of renewable energy sources. The depiction below shows objectives of the National Action Plans for the development of renewable energy sources in the individual countries. However, these action plans are binding only up to 2020. The German Federal Government drafted objectives in its energy concept that go beyond 2020 regarding the share that renewable energy sources should take up in gross electricity consumption.

Diagram 1: Targets for the expansion of RES in the EU according to the National Action Plans*



Note: Switzerland has no specific targets for 2020 and can therefore not be depicted.
Source: [EEA], [Eurostat]
** RES: Renewable Energy Sources*

(3) The development of renewable energy sources will defer the structure of electricity generation. Moreover, the characteristics of the market will undergo appreciable changes because of the increasing proportion of supply-dependent and volatile production. Electricity generation and electricity demand will increasingly drift apart in time and space. In the coming decades, all of that will give rise to considerable **challenges**. In essence, these can be divided into three categories:

- long-term security of power supply,
- network expansion and congestion management in the electricity grid (including dealing with oversupply situations), and
- provision of ancillary services.

In the coming paragraphs, these challenges are described in-depth with a subsequent extrapolation on how international storage could contribute to problem solving.

3.1 Drifting apart of electricity supply and demand

(1) Below, the assumed development of renewable energy sources in Germany is depicted. For this purpose, we focus on the pilot study of the Federal Government [DLR 2011], which shows a long-term development path for renewable energy sources.

Diagram 2: Expansion pathway of renewable energy sources in Germany up to 2050

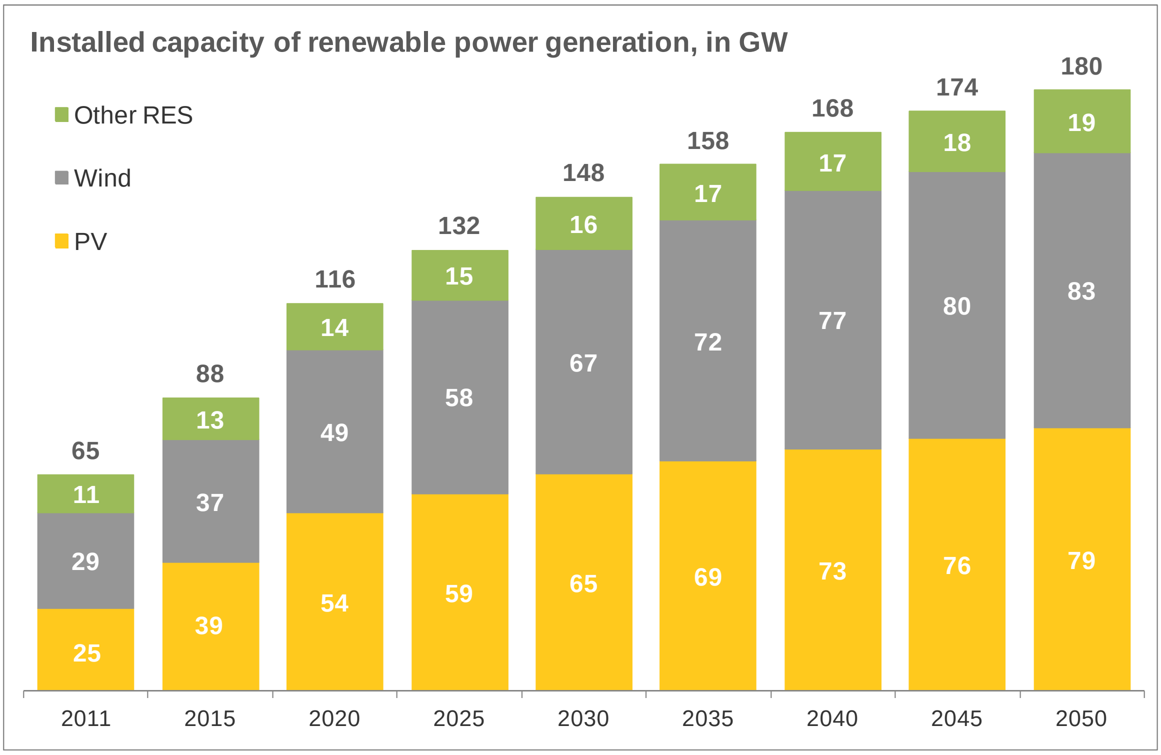
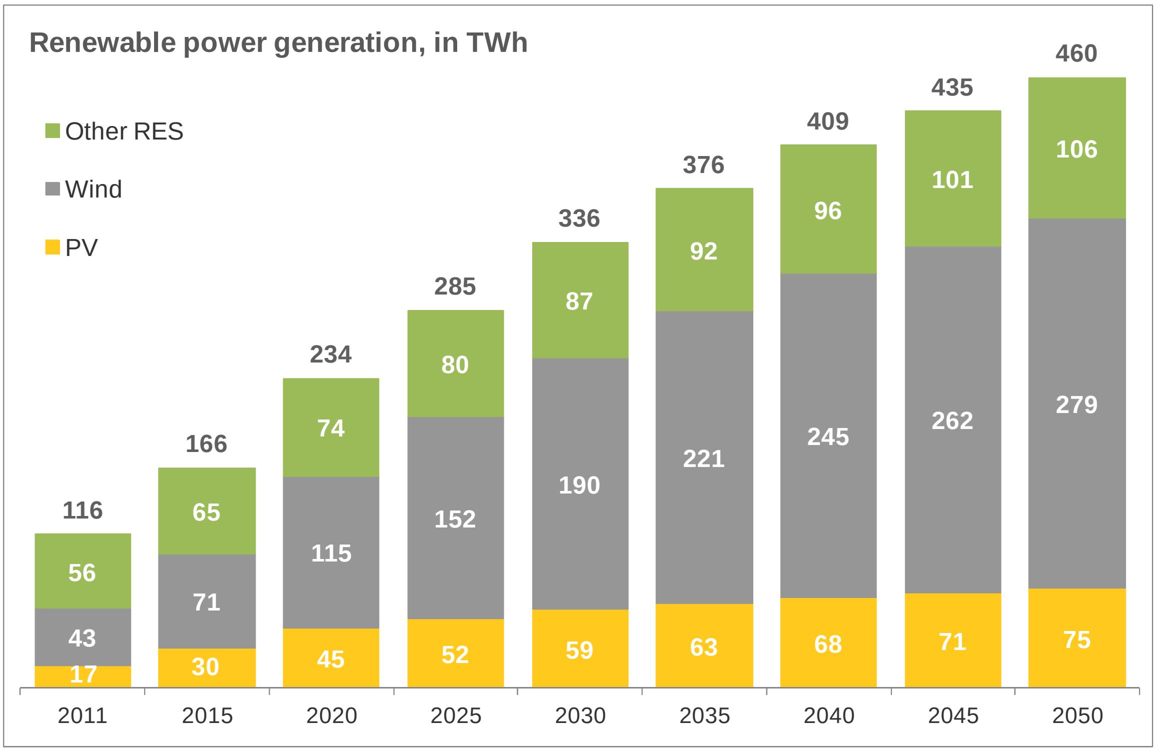


Diagram 3: Electricity generation through renewable energy sources in Germany up to 2050



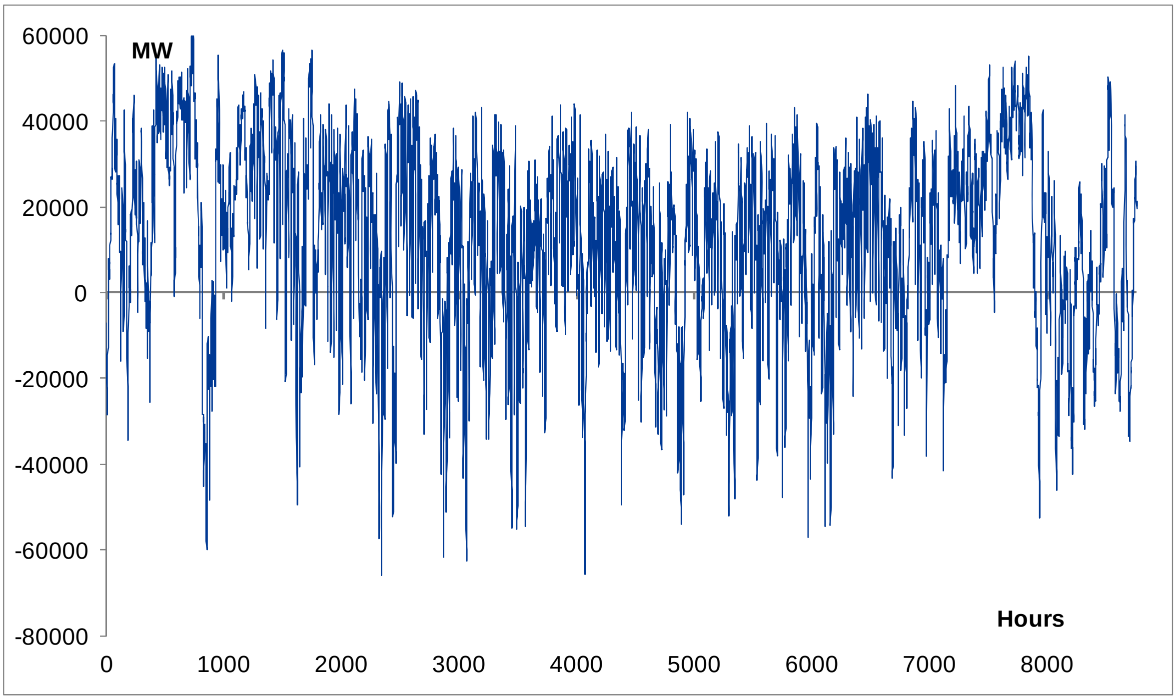
Source for both illustrations: [DLR 2011, scenario A for wind and remaining EP, scenario B for PV]

(2) If the expansion pathway shown here is taken as basis, then by taking into consideration "usual" supply profiles for particular energy sources, the implication in 2050 will be a **residual load** for conventional generation and controllable renewable electricity generation, which is shown in the figure below. The residual load is the load, which after deduction of the fluctuating renewable supply, still needs to be covered.

The required assumptions regarding **electricity demand** are documented in Diagram 29 in the appendix to this study.

It becomes clear that in a multitude of hours, renewable generation exceeds the respective load in the concerned timeframe (residual load negative in Diagram 4: column down). In these cases, Germany produces more electricity from renewable energy sources than it consumes.

Diagram 4: Residual load in Germany in 2050



Explanation: If the residual load is negative, Germany produces more electricity from renewable energy sources than it can consume itself in this hour

Source: Own calculations

(3) Diagram 5 shows how big the **oversupply** or **undersupply** of **renewable energy** in Germany will be up to 2050, seen in perspective.

At the same time, must-run capacities in conventional power plants (including cogeneration, i.e. combined heat and power), which are necessary to maintain system stability, have already been taken into account. According to a recent study by the German Transmission System Operator [TSO 2012] must-run capacity to ensure system stability is currently about 20 GW. We assume that this must-run capacity in the German electricity system can be reduced to 5 GW by 2050.

It becomes apparent that, for example, in 2030 in about 1,100 hours a year, more electricity will be produced in Germany than will be demanded at these points in time in Germany.

It is possible that in 2050, in approximately 2,200 hours per year, renewable power generation could exceed electricity demand in Germany. In some hours, the excess amounts to up to 60 GW. The potential electricity surplus amounts to about 38 TWh or about 8% of the electricity consumption in 2050.

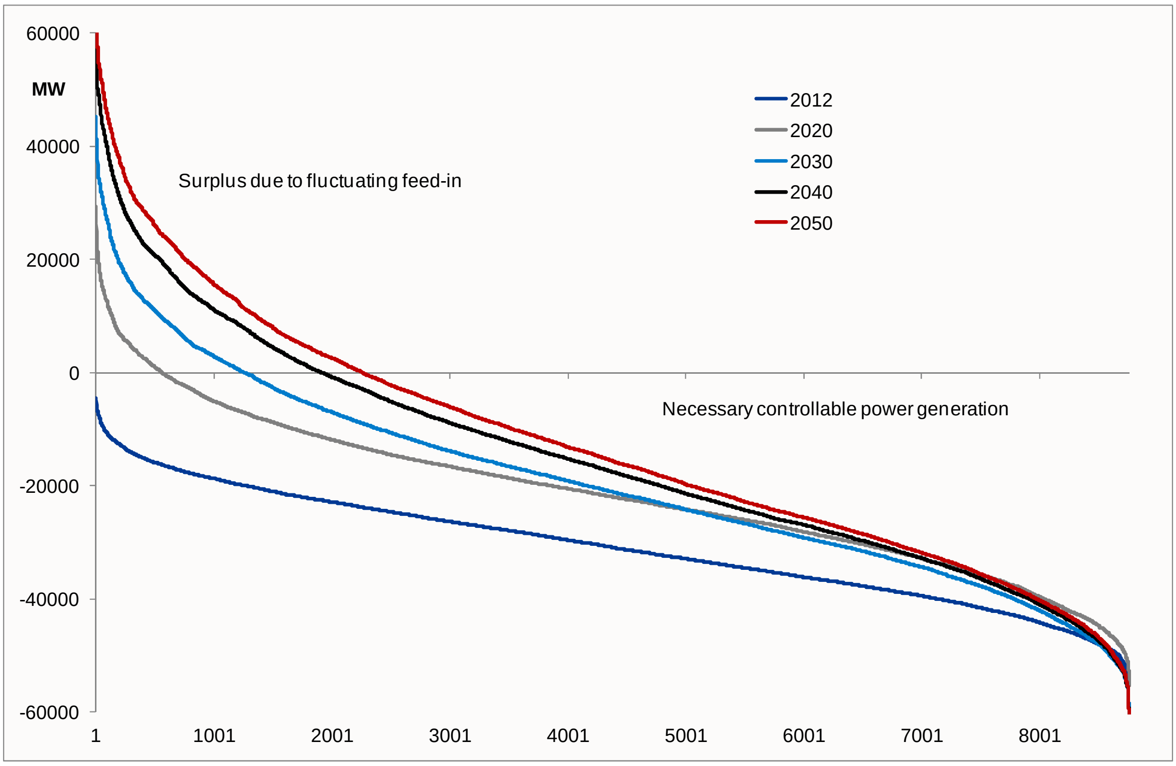
If it were possible to utilise the surpluses of up to 12 GW in other countries, then about half of the electricity surplus could be used.

A full utilisation of this surplus seems, from today's perspective, to be not viable economically, simply because the effort of using the "last kilowatt hour" is so disproportionately large.

In addition to these statements regarding the renewable "surpluses" in the considered future, the following also becomes very clear from Diagram 5: in the majority of hours per year, also in 2050, controlled power plants such as biomass or conventional thermal power stations will still be required to provide the needed capacity. Storage systems have a role to play here.

Even nowadays, because of insufficient transmission capacities, temporary oversupply situations occur in some control zones that require intervention by the system operator. The evaluation is based on a Germany-wide analysis without considering network congestion (the concept of "copper plate Germany").

Diagram 5: Yearly load duration curves of surpluses due to fluctuating electricity supply in Germany from 2012 to 2050

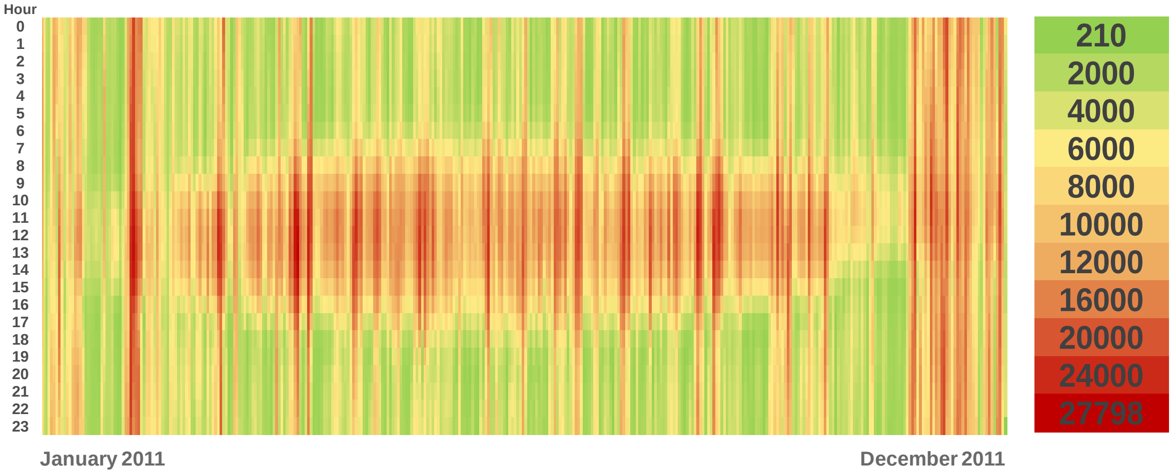


Explanation: Inverse representation of Diagram 4: if the renewable energy supply exceeds the respective power requirements of the applicable hour, the curve then lies above the zero line.

Source: Own calculations

(4) So far the presentations already qualified the challenge from fluctuating electricity supply. The following presentation shows an example based on the electricity supply of 2011, at what time of the day and when in the course of the year oversupply situations are to be expected. The typical photovoltaic supply profile is clearly discernible: especially from spring to autumn, a daily maximum supply phase occurs between 9 am and 5 pm. In addition, windy phases do occur every season (here: late January and December 2011), which then usually mean a high supply for several days (and nights) in succession.

Diagram 6: Inflow from wind and PV in Germany 2011 (in MW)



Explanation: The X-axis shows the time of year, the y-axis the day time. The colour indicates the amount of supply from wind and PV.

3.2 Long-term security of power supply

(1) The entire power system, which in future will be increasingly linked up beyond national borders, must at all times keep up with supplying the corresponding capacity through power generation when the consumer draws capacity from the system. This has the following implications for the future: when power generation from supply-dependent wind and solar capacities is not available, capacity must then be provided from alternative installations or, during such phases, electricity demand must be reduced on the available number of installations. Because electricity demand reacts quite inelastic to short-term price signals, it is absolutely essential that electricity demand in the system is covered by backup power plants for such scenarios. The following table shows the installed total capacity of power plants in Germany, which will increase significantly until 2050, because the volatile energy production hardly contributes towards guaranteed capacity.

Table 1: Development of installed capacity and peak load in the German electricity system in 2000, 2011 and 2050

[GW]	2000	2011	2050
Total gross installed capacity	123	166	231
Installed capacity of conventional power plants	108	101	50
Installed capacity of renewables	15	65	181
Peak demand*	75	76	ca. 75*

** Estimate based on a constant- load profile.*
Sources: [Prognos AG 2011], [DLR 2011, scenario A with PV-expansion pathway scenario BB]

(2) The increasing share of renewable energy sources in the overall system will exert a telling influence on the wholesale electricity prices through the **merit-order effect** in the future. If a growing proportion of power supply stems from marginal cost-free power generating sources, then conventional power plants that are used less can occasionally no longer be operated economically. These facilities would be shut down in compliance with strict business-administrative rules. Furthermore, in such a situation investment in new facilities will also stay away, because the capital costs alone cannot be redeemed solely from selling electricity. This situation is referred to as the **missing money problem.** Already in the middle of 2012, the reluctance to invest in large power plants can clearly be discerned. Older power stations are currently not modernised any more, but only operated for as long that they can earn their operating costs.

(3) Not least for this reason is the discussion in full swing on **sustainable market instruments,** which guarantee the capacity requirements. This is especially of significance in the light of further nuclear power plant shutdowns. Such capacity mechanisms can have the form of either price instruments (peak-load pricing) or of quantity instruments (capacity auctions, options markets for capacities, investment premiums, etc.). The current capacity market conclusions, which are mostly pure energy-economic related, must not ignore network-technical interests that guarantee security of supply. The capacity market discussion should address in particular ancillary services, which on a local, regional and national level necessarily require protection as elaborated in chapter 3.4. However, they all have in common that the regulatory effort to bring capacities to the market efficiently and effectively will be signifi-

cant.[2] The need for such mechanisms and their compatibility with the European internal electricity market are currently under discussion.

(4) Temporary relief would also provide a suitable **demand-side management,** which means a stronger control of load-demand issues. If it succeeds that large consumers can react variably to supply peaks or congested, i.e. bottleneck situations and power consumption is allowed to be controlled by this, then the essential security of supply capacity can be reduced. Thus it would be possible to reduce the essential installed reserve capacity and to minimise the occurring costs. However, based on current knowledge, the possibilities of demand-side management are limited.

3.3 Network expansion and congestion management in the electricity network

(1) In the past, power plants have been built mostly in regions with a high demand in order to minimise **electricity transport** and network distribution losses. Electricity generation installations were built in the vicinity of and because of brown or hard coal deposits, therefore, many large consumers also settled in the same locality.

In the past, electricity in Germany was consumed within a radius of at average less than 100 km to the respective power plants. The development of renewable energy sources, however, is based on the natural supply of resources such as average wind speed and solar radiation. To be able to meet the future power-supply needs mostly from renewable sources, both the demand, as well as the strain on the **trans-regional electricity transmission capacities** will increase.

Wind power needs to be transported from northern Germany to the south and west of Germany. At midday, however, also photovoltaic electricity must be transported from the south to the north. Today's electricity networks were not designed to cope with the transportation of future electricity production.

(2) Currently, the second draft of the electricity network development plan 2012 (“Netzentwicklungsplan Strom” - NEP) presents nearly 1,200 km optimisation and reinforcing measures in existing

2 A good overview of capacity mechanisms is provided by a publication of the German Renewable Energy Federation (BEE). [BEE 2011]

transmission routes, as well as around 700 km of new construction routes for the so called “starting grid”. In the network development plan, the starting grid emulates the status quo of the German electricity grid, but also includes lines that are already under construction or have already been approved. Furthermore, network lines were identified through network analyses that are required for the transportation of future electricity transmissions (2012 to 2022). The Lead Scenario B 2022 (guiding reference) has to do with the entire cabling process on the existing linkage structure of 1,300 km, the new lines for existing routes of about 2,800 km, the switch-over from AC to DC current of about 300 km and new DC lines of approximately 2,100 km. [NEP 2012].
However, due to the delays in the expansion of transmission lines in Germany the materialisation of essential projects within the required deadlines hangs in the air.

(3) The need for a suitable **network-congestion management** increases substantially due to the ongoing delays in the network expansion. Network congestions are currently being resolved through the cost-based redispatch procedure. For this purpose, in order to balance emerging costs, producers are shut down before congestion occurs - more exactly, before the load increases. After a congestion situation exactly the reverse takes place. This procedure is used however only for the short-term elimination of congestion situations and serves only as a transitional measure until the implementation of appropriate reinforcements or network expansions are in place. The cost of congestion management is transferred to the network charges of the electricity customers.

3.4 Provision of ancillary services

(1) The necessity of a **balanced equilibrium** of electricity feed-in and extraction has already been discussed in the context of long-term security of power supply. This criterion is decisive in the **short term** for a safe and reliable **operating system**. For this purpose, power plants or large consumers are integrated into a control system, which, in the event of short-term balance deviations in supply and extraction, restores the equilibrium again in a matter of seconds and minutes. This is also called the allocation of **operating reserve** or primary balancing or secondary control and is of short-term nature compared to the security of power supply described above. The allocation of operating reserve is an ancillary service, without which blackouts would be inevitable. These ancillary services are nowadays mainly provided by conventional power plants, but also by pumped-storage hydroelectric installations.

(2) In addition to the operating reserve, other **ancillary services** are necessary to guarantee the operation of the electricity system and the quality of power supply without frequency and voltage fluctuations. Included in these ancillary services, which need to be made available locally, are the voltage and reactive power regulation, the provision of short-circuit power and the black-start capability of power plants, whereby nowadays especially the pumped-storage hydroelectric installations with its controllable generation and loading capability play an important role in the network reconstruction concepts.

It is estimated that nowadays the need exists for 15 to 20 GW of conventional capacity for the allocation of operating reserve and ancillary services. In order to continue the efficient development of renewable energy sources, it must be ensured in the future that all ancillary services are conducted also by renewable energy technologies, i.e. including other technical measures. Only under these conditions can the **conventional "must-run" capacities** that are still essential today be reduced. One of the major challenges is therefore to prepare the renewable energies technologically for these tasks, as well as the market for ancillary services for the coming general scheme of things making out the renewable energy era.

3.5 Potential solutions for the integration of renewable energy sources

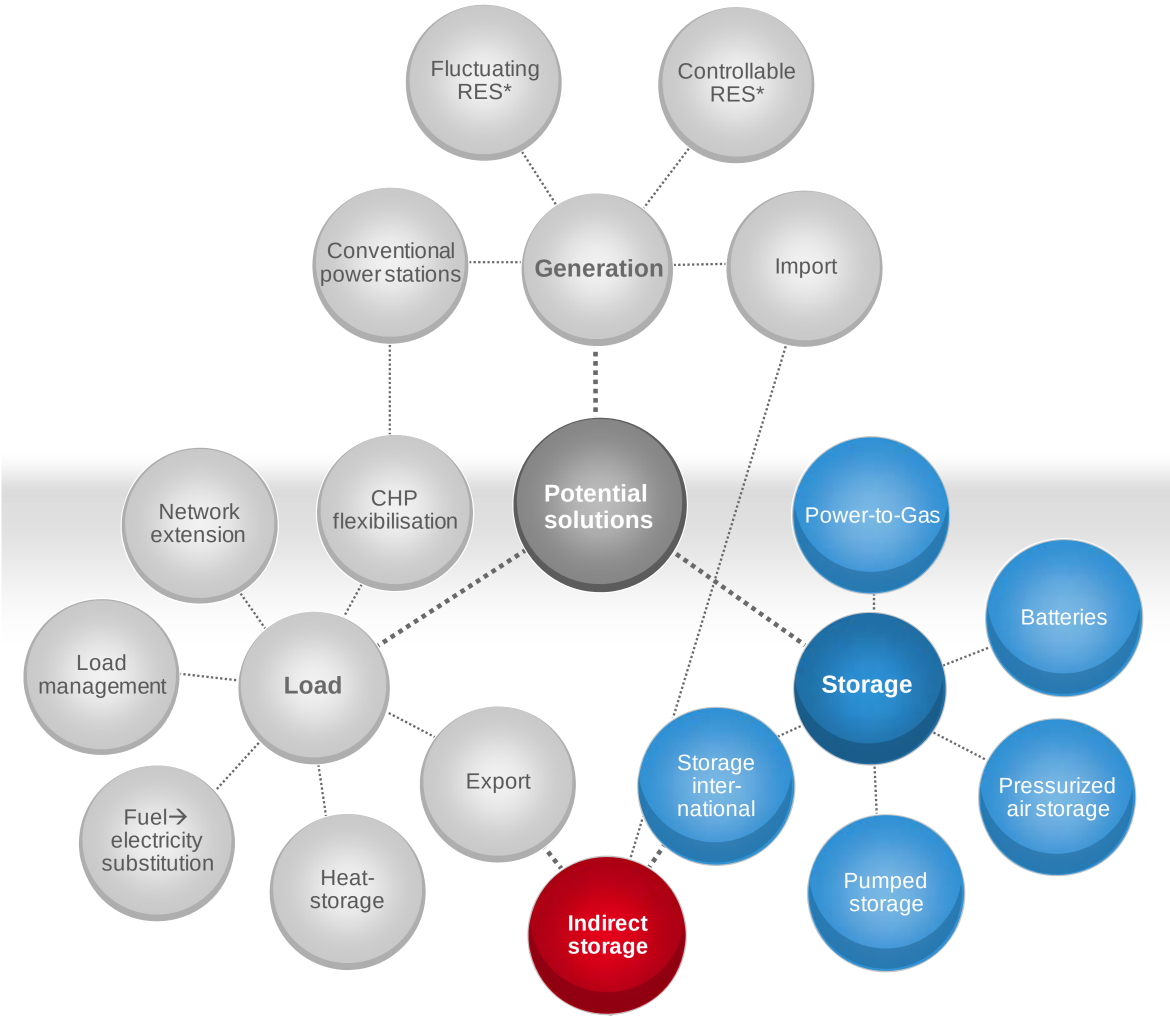
(1) As already exemplified in the previous sections, the future electricity generation in Germany will be marked by a high component of fluctuating installations implying a string of challenges for the electricity system. The three most important challenges are long-term security of electricity supply, dealing with oversupply situations and security for the system stability.

(2) The following illustration shows a **mind map** in this respect with potential solutions for the integration of renewable energy sources and the guaranteeing of security of supply. Potential solutions fall in the categories of generation, load and storage. The present study focuses on **storage** in accordance with its assigned task**.**

(3) An important potential solution in the area of storage, as well as load, is the utilisation of international storage facilities with the help of interconnectors. This enables the utilisation of surplus energy, but also the provision of energy at times of low production capacity by renewable energy sources. The so-called **indirect**

storage achieves moreover the highest level of efficiency of nearly 90% and in this respect is the most efficient way of storage. In this type of storage, for example, electricity from German surpluses is consumed directly in Scandinavia, while the local storage is spared. At a later stage more electricity can then be generated in Scandinavia from water in the hydroelectric installations, e.g. to deliver electricity to Germany (graphically illustrated, see Appendix, Diagram 30). In this type of storage, losses from pumping operations are avoided as they occur in pumped-storage hydroelectric installations. Losses due to the two-time transmission of power by interconnectors apply (two times 5%). This makes indirect storage so efficient. In the depicted comparison of options for the integration of renewable electricity in Table 2 only the investment costs in the case of interconnectors are indicated, because, for the time being, the construction of power plants is not required for the use of this potential.

Diagram 7: Mind map of potential solutions for the integration of renewable energies into the electricity system



Source: Own presentation
** RES: Renewable Energy Sources. Also the facilities for the use of fluctuating energy sources like wind and solar are adjustable to a limited extent, but essentially "downwards", i.e. they can be turned off.*

(4) The following table compares solution options for the integration of renewable energy sources in terms of their cost and other technical parameters.

Table 2: Comparison of options for the integration of electricity from fluctuating renewable energy sources

Technology	Interconnectors (indirect storage)	Heat storage systems	Adiabatic compressed air energy storage	Pumped storage hydro plant	Hydrogen/ Methane	Batteries (e.g. Electric vehicles)	Load management (industry)	Load management (households, tertiary sector)
Expected marketability	today	today	2010 to 2020	today	2020 to 2030	2015 to 2020	today	2020
Implementation time	approx. 8 years	2 to 3 years	3 to 5 years	10 years	3 to 5 years	1 year	1 to 10 years	1 year
Application potential	1,4 GW per cable	2,2 to 3,6 GW_{el} (positive) 4 to 18 GW_{el} (negative)	> 700 caverns	2,7 GW_{el} (planned until 2020)	unlimited	3 GW_{el}[1]	2 GW_{el}	3 GW_{el}
Range (in hours)	weeks to months	4 to 24	8 to 16	4 to 8	seasonal	1 to 8	2 to 8	1 to 24
Efficiency (power-to-power)	ca. 90% (from Germany to Germany)	95% (heat-to-heat)	60 to 70%	70 to 80%	30 to 40%	75 to 95%	-	-
Investment costs (EUR/kWel)	1,400	640 (positive), 120 to 350 (negative)	1,000 to 1,500	1,000 to 2,000	1,500 to 3,000	1,000 to 2,000	depending on the process	depending on the process
Lifetime	20 to 40 years	40 to 60 years	40 years	>100 years	30 years	3,000 cycles	-	-
Acceptance	medium	good	medium	low to medium	medium to good	good	medium	medium

1 Considering 1 Mio. E-vehicles (each with a load of 3 kW) connected to the network at the same time. Depending on the degree of connectivity, 2 to 3 Mio. E-vehicles could be expected.

2 This estimation by Prognos AG describes the situation for Germany. Different estimations concerning the acceptance of pumped storage do exist in the partner countries.

3.6 Summarised assessment

(1) The briefly outlined challenges specified in this chapter for the electricity system occur sooner or later in the development of renewable energy sources in all the scenarios. Since many of these issues correspond with the development of fluctuating renewable energy sources, the case becomes even clearer the sooner even higher proportions of **volatile renewable production** (wind, PV) penetrate the market. It seems from today's perspective that the mentioned technical issues are solvable; the question however remains whether there are sufficient incentives for entrepreneurial investment.

This can be done, however, by bringing about the appropriate changes in the shape of the market and by promoting incentives for the technical development.

(2) The tempo sought by the Federal Government in the **implementation of the energy transition** requires so to speak a high tempo in which the adjustment of the market design, the technical development and the provision of necessary infrastructure must follow suit. In spite of all efforts, the complexity of challenges still contains a significant implementation risk that is often neglected in the assessments. Many of the issues to be resolved with regard to the market design and the infrastructure projects also touch upon interests on a European political level and of the European electricity network, which increase the risks of delay even more.

(3) Due to the challenges in the energy transition, the **role of regulation** of the electricity market will continue to increase. Large sections of the market will be subjected to external interference. Therefore significant efforts must be made to obtain as many **elements of competition** in the electricity supply, which will make way for a differentiation of structures and actors. In particular, renewable electricity generation enters the limelight, which is characterised by high capital and fixed costs, but rather low variable costs. For this reason, they cannot survive in the current market structures without secure sources of revenue and are consequently dependent on regulation and a fundamentally different market design. The challenge will consist therein to develop a market in which production techniques of any kind can occur in equal competition and to ensure the most efficient and effective power supply in the long term.

(4) From the perspective of the focus of this study it should be kept in mind that **storage** can make an important contribution to the solution of long-term security of electricity supply and to ancil-

lary services. Comparing domestic storage, e.g. compressed-air energy storage or pumped-storage hydroelectric installations, with international solutions (water-storage facilities including the necessary development of interconnectors, see Table 2) it becomes clear that interconnectors, at least when compared with other storage options, perform very well with regard to efficiency and investment costs. On the other hand, they can, in contrast to domestic pumped-storage hydroelectric installations, make contributions only in the direct physical environment (approx. up to about 200 km) to local ancillary services. These aspects were however not analysed in depth by the present study.

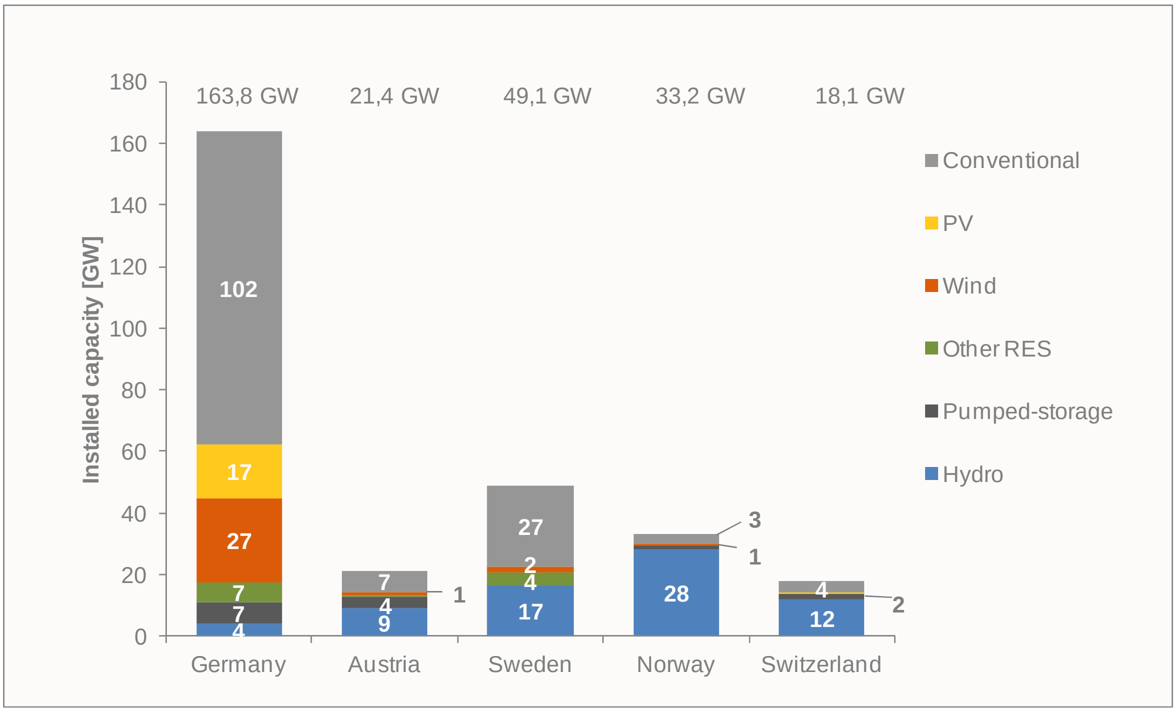
In comparison, compressed-air energy storage systems and especially thermal-energy storage systems can be obtained at a relatively low cost. As was already exemplified previously with Table 2, especially compressed-air energy storage systems are clearly much less efficient than an electricity association with Scandinavia or the Alpine countries. In particular, there are only two options that allow energy storage over several days or even weeks and its corresponding slow release again: hydroelectric storage facilities in Scandinavia and the Alpine region, as well as hydrogen, i.e. methane storage. Judged from the present perspective, when weighing up these two alternatives, **international storage** remains **more efficient and more cost effective.** For this reason, the present study continues to focus on the storage option and examines below in a differentiated way how, through interconnectors, the technical and economic potentials for the utilisation of indirect storage are to be judged.

4 Hydroelectric installations in selected European countries - status quo and prospects

(1) This chapter focuses on the **hydroelectric installations** in the countries under survey. At first we present the structure of the installed capacities of the electricity production followed by the composition of the net electricity production. Subsequently, in separate sub-chapters, the situation of hydroelectricity in these countries will be dealt with specifically.

(2) Diagram 8 presents the **structure** of the installed **capacity** of the electricity generation for the year 2010. This exemplifies that Sweden and Germany with more than 50% have a high proportion of conventional power plants. Typical for Germany are fluctuating renewable energy sources like wind and sun. Sweden, on the other hand, is characterised by its hydroelectric installations (34%). In Austria hydroelectric installations have the highest proportion of the installed capacity with approximately 43% followed by conventional power plants with approximately 33%. The Norwegian power plant structure is also characterised by a large proportion of hydroelectric power plants (about 85%). Here thermal power plants make out only about 9%. Alongside Norway, Switzerland mainly has hydroelectric installations with around 66%, followed by conventional power plants with a share of about 22%.

Diagram 8: Structure of the installed capacity of electricity generation in 2010 in GW

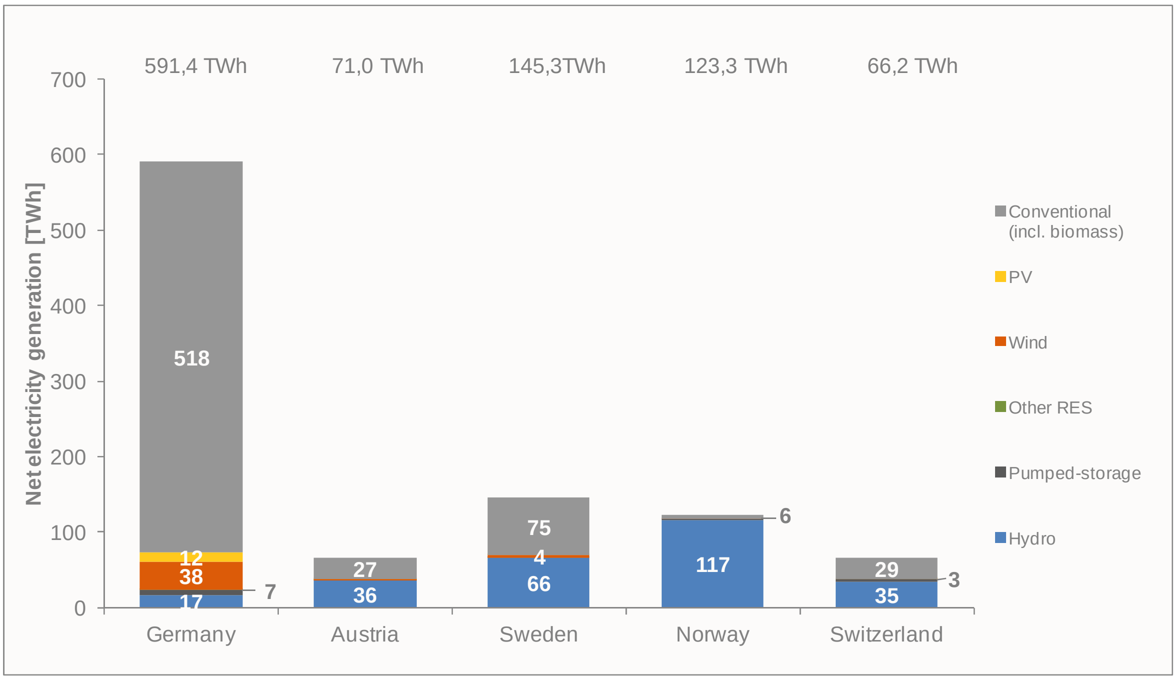


Information on Switzerland: numbers on pumped-storage hydropower and other hydro power are partly based on calculated values. Waste-incineration plants are considered in the electricity statistics of Switzerland to be up to 50% of a renewable electricity kind. Information on Austria: information on PV, wind, pumped-storage hydroelectric installations and other hydroelectric power is partly based on calculated values.

Source: [Eurostat], [BFE, 2011c], [E-Control 2012], [Eicher]

(3) In addition to the structure of the installed capacity, an overview now follows of the **net electricity generation**. Diagram 9 gives a graphic overview for 2010. Typical for Germany is the electricity generation of about 591 TWh, approximately 83% of which was generated by conventional power plants. Besides this, wind takes up a share of 6%, followed by biomass with 4% and hydropower and photovoltaic, each with about 3%. Sweden produced about 145 TWh in 2010, which originated mostly from conventional power plants (about 52%), as in Germany. The share of renewable energy sources is thus approximately 48% and was generated mostly from hydroelectric installations. About 94% of Norway's electricity is produced in hydroelectric installations, so that the share of conventional power plants is only about 4%. Austria's share of hydroelectricity is about 51%, followed by conventional generation of about 35%. In Switzerland, the structure of electricity generation is similar to that in Austria: hHydroelectric installations have a share of about 53 %, followed by conventional generation of about 42%.

Diagram 9: Net electricity generation in 2010 in TWh



Information on Switzerland: information on pumped-storage hydroelectric installations and other hydroelectric power is partly based on calculated values.
Information on Austria: information on PV, wind, pumped-storage hydroelectric installations and other hydroelectric power is partly based on calculated values.

Source: [Eurostat], [BFE, 2011c], [E-Control 2012], [Eicher]

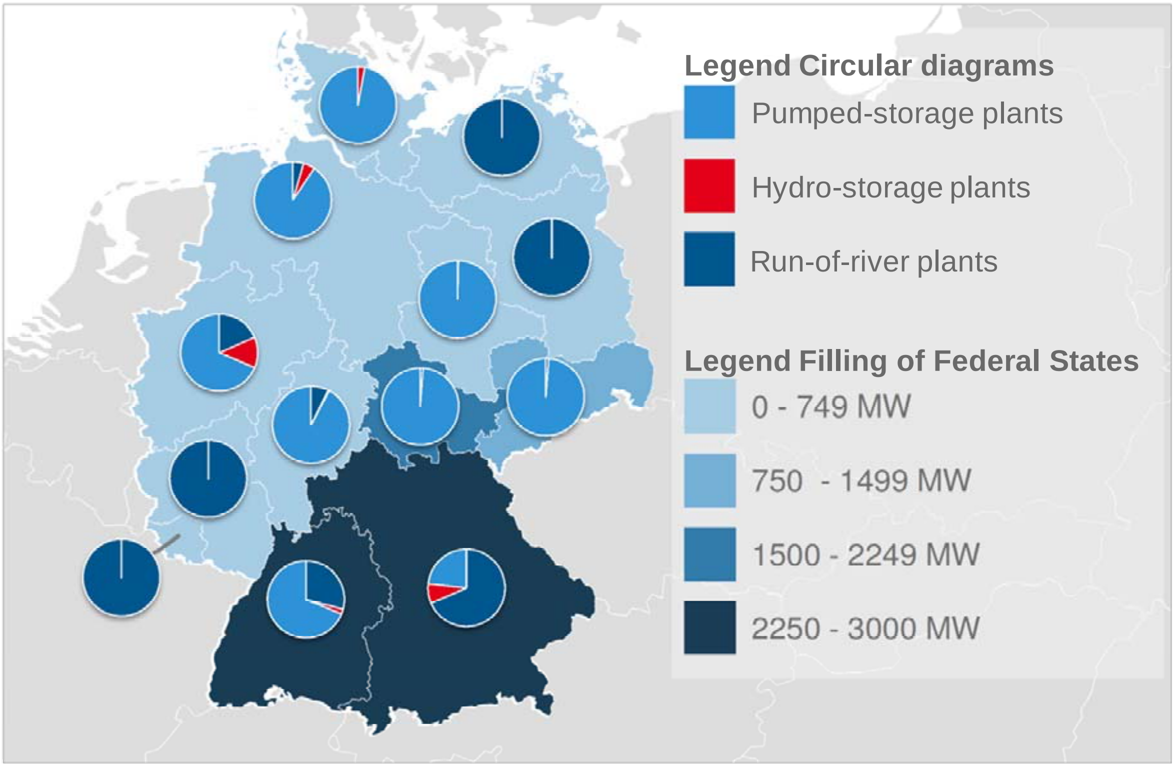
4.1 Germany

(1) **Hydroelectric installations** account for a share of around 6% of installed capacity in Germany with approximately 9,790 MW and with approximately 23,250 GWh for about 3% of the net electricity generation.

(2) Diagram 10 gives a graphic depiction of the installed capacity in MW of hydroelectric installations in each **German Federal State.** The filling of each Federal State shows the quantity of installed capacities in MW and the respective pie chart the share of the type of hydroelectric installation (run-of-river, hydro-storage and pumped-hydro storage facilities). Baden-Württemberg has a particularly large number of hydroelectric installations (about 2,900 MW) and Bavaria (about 2,500 MW), followed by Thuringia (1,500 MW) and Saxony (1,200 MW). All the other Federal States show installed capacities of less than 430 MW.

(3) **Run-of- river hydroelectric plants** account for about 2,934 MW of which about 1,684 MW are allotted to Bavaria and about 843 MW to Baden-Württemberg. The installed capacity of **hydro-storage plants** is approximately 335 MW. These are located mainly in Bavaria (about 202 MW), Baden-Württemberg (about 60 MW) in North Rhine-Westphalia (about 79 MW) and Lower Saxony (12 MW). The **pumped-storage hydroelectric plants** in Germany have a capacity of around 6,521 MW. These are located mainly in Baden-Württemberg (about 2000 MW), in Thuringia (about 1,520 MW) and in Saxony (ca.1.170 MW). The **hydro-storage capacity** in Germany at maximum filling level lies around 0.05 TWh[3].

Diagram 10: Hydroelectric plants in Germany, 2010



Source: Own representation according to [BDEW 2011]

3 Source for the capacity of pumped-storage hydroelectric plants is [SRU 2011]. Prognos estimated the capacity of the hydroelectric plants.

(4) The following Table 3 summarises the capacity and the working volume of all the hydroelectric plants together in Germany.

Table 3: Hydroelectric plants in Germany, 2010

Type	Capacity [MW]	Generation [GWh]
Hydroelectric power plants	**9,790**	**23,248****
- Hydro storage power plants	335*	691**
- Pumped hydro storage	6,521*	6,799**
- Run-of-river power plants	2,934*	15,758**

*Source: * [BDEW 2011], ** [Destatis]*

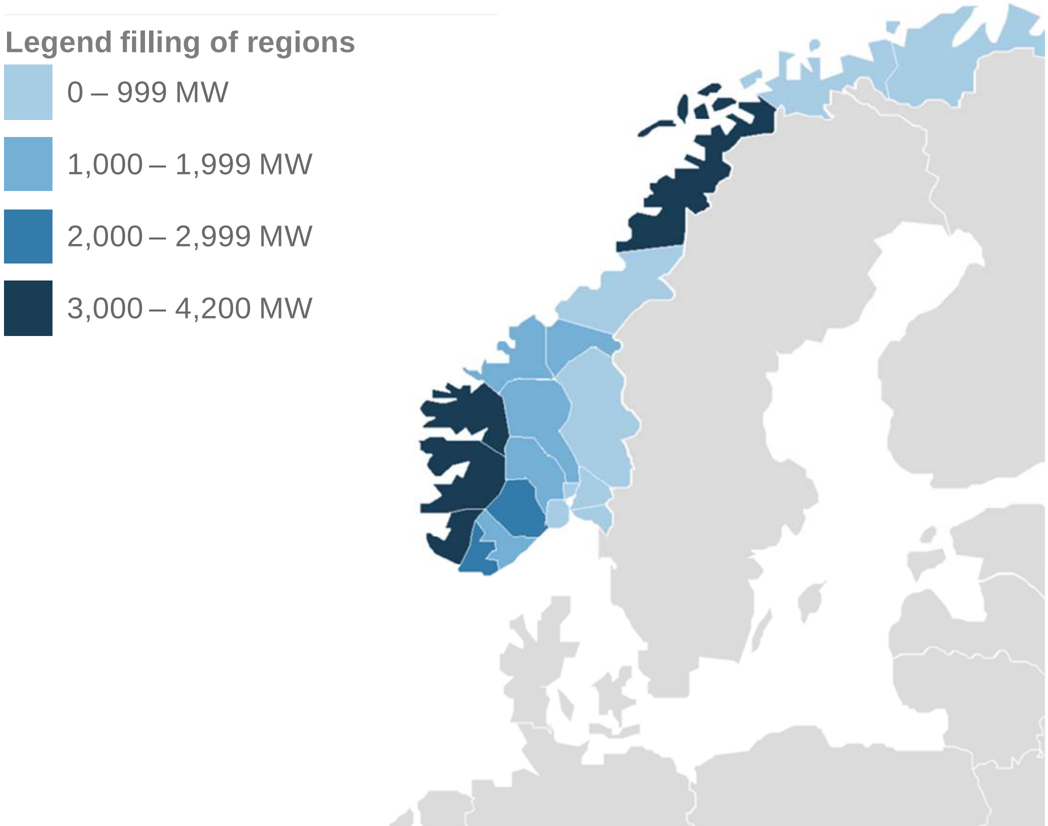
(5) Several **new hydroelectric plants** are to be put into operation by 2020. They have a total capacity of about 2,770 MW. These include the fifth turbine of the run-of-river type hydroelectric plant at Iffezheim (38 MW), a French-German joint venture power plant and four new pumped-storage hydroelectric installations (Waldeck II (extension), Atdorf, Simmerath/Rursee, Nethe/Hoexter), some of which already have been approved. In addition, five other new pumped-storage hydroelectric installations with a total capacity of approximately 2,150 MW, together with an expansion of 200 MW are planned.[4] If all the mentioned power plants would materialise, a total capacity of approx. 5,100 MW would subsequently be created.

4.2 Norway

(1) **Norway's electricity generation** is characterised by a high proportion of hydroelectric power plants of approximately 95%. Due to topographical conditions, the regions in Norway distinguish themselves through the installed capacity of the existing hydroelectric plants. The following Diagram 11 gives a graphic depiction of the installed capacity in MW of Norway's hydroelectric installations in each province. The largest component of installed capacity is in Hordaland in south-western Norway with an installed capacity of around 4,144 MW.

[4] Expected start-up of the planned pumped-storage hydroelectric plants: Schweich 2017, Jochenstein/Energy storage facility Riedl 2018, Heimbach 2019, Talsperre Schmalwasser 2019, Blautal k.A., Forbach (Extension) k.A. [BDEW 2012]

Diagram 11: Installed capacity of hydroelectric plants in the individual provinces of Norway



Source: Own presentation according to [NVE 2009]

(2) The **installed capacity** in 2010 was approximately 31,004 MW. Hydro-storage plants make out a particularly high component of approximately 75%, followed by run-of- river type hydroelectric installations of approximately 20% and pumped-storage hydroelectric plants of approximately 5%. It should be taken into consideration that the installed capacity depends on the water level, and the waterfall height and is therefore not always fully retrievable.

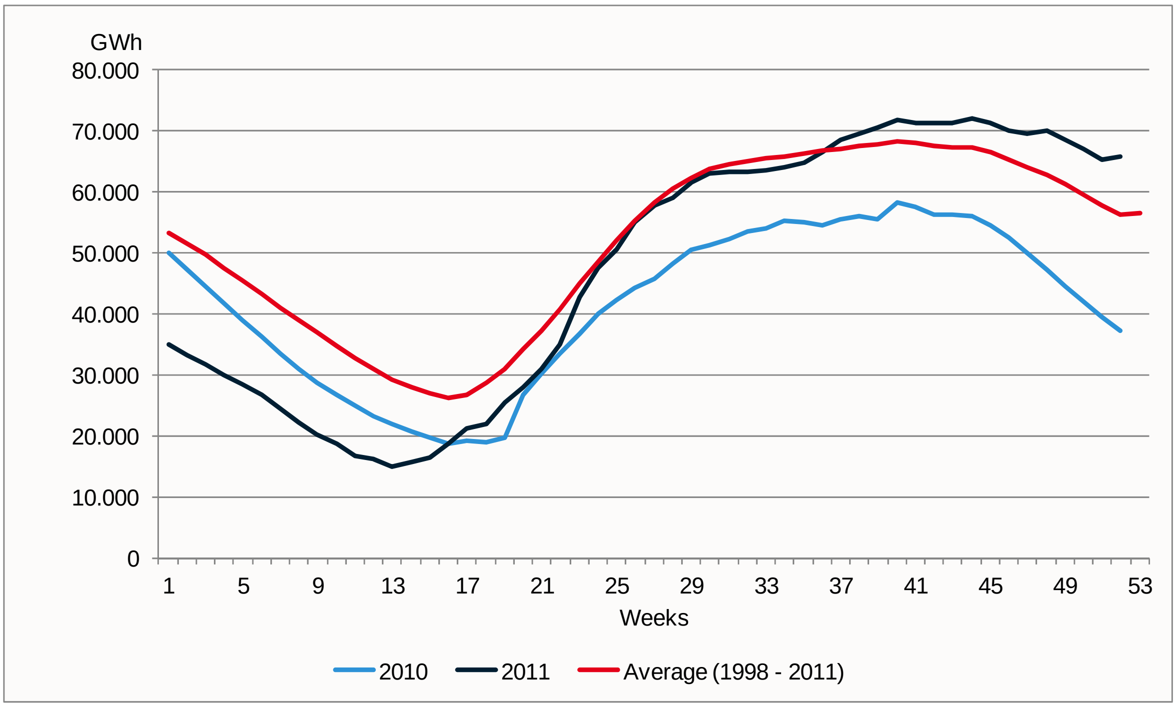
Table 4: Hydro-storage and pumped-storage hydroelectric plants in Norway in 2010

Type	Capacity [MW]	Generation [GWh]
Hydroelectric power plants	**31,004**	**116,946***
- Hydro storage power plants	23,405*	85,000**
- Pumped hydro storage	1,344*	
- Run-of-river power plants	6,255**	

*Sources: * [Eurostat], **[SINTEF]*

(3) The **filling level of reservoirs** is dependent on inflows from rain and melting glaciers. In this regard, different hydrological conditions lead to different filling levels in the reservoirs. Diagram 12 gives a graphical depiction of the filling level in the reservoirs in Norway over several years. The maximum working volume of the reservoirs is about 81.9 TWh. The filling level of the water storage facility has an annual fluctuating course with a low filling level in April and a high filling level in September/October. On average between 1998 and 2011, the lowest filling level was about 26.2 TWh, and the highest around 68.2 TWh. One can distinguish between water-poor and water-rich years due to the different conditions. For example, low glacier melting and low rainfall in 2010 led to a low filling level in the winter of 2010, which, on the other hand, resulted in a very low filling level in the spring of 2011. What is even more, the demand for electricity in winter is higher than in summer, as Norway's heating demand is mainly covered by electricity and the darkness requires more electricity for lighting.

Diagram 12: Filling levels of the reservoirs in Norway, weekly values, in GWh

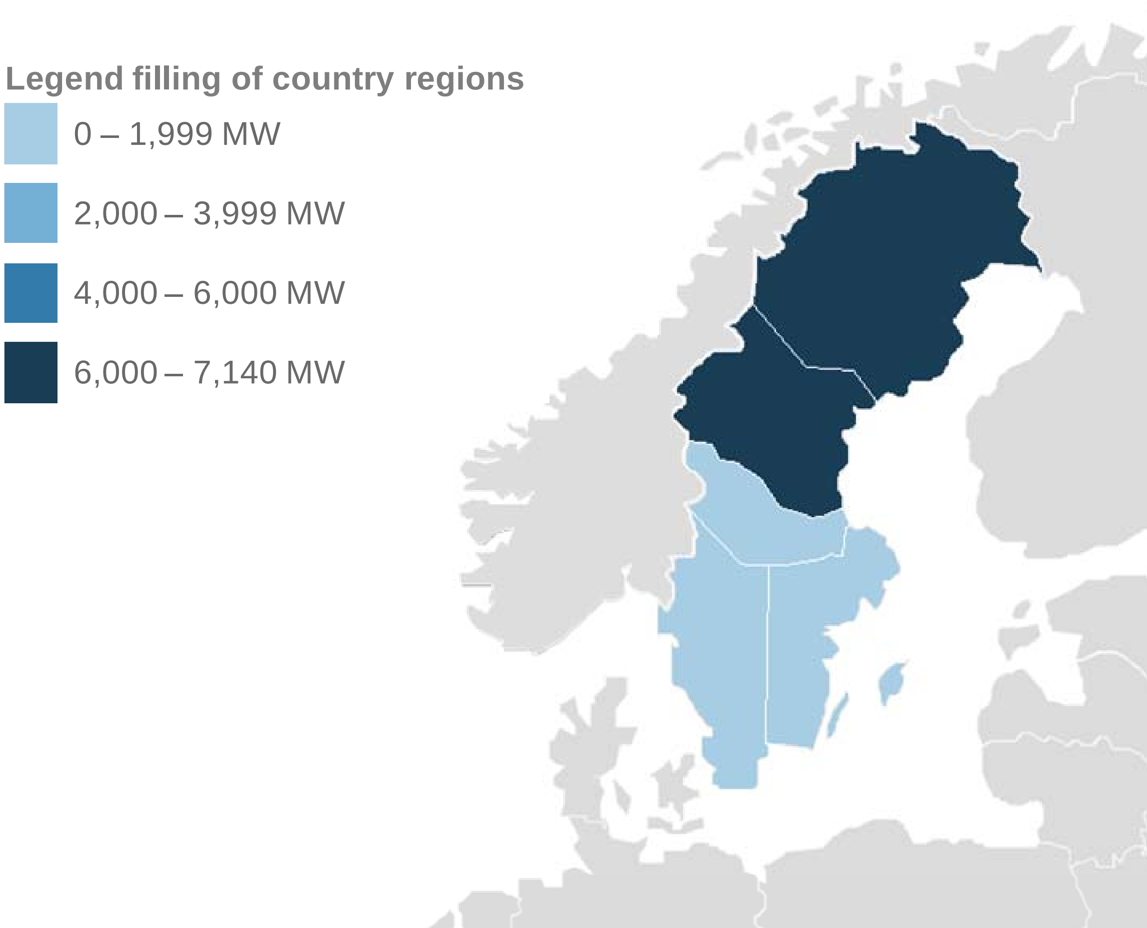


Source: Own presentation according to [Nord Pool Spot]

4.3 Sweden

(1) **Sweden's** share of hydroelectricity in the net electricity generation is about 46%. Most of the hydroelectric plants are located in the north of the country, especially in the upper Norrland with an installed capacity of approximately 7,140 MW (see Diagram 13). These hydroelectric plants are located mainly on the largest rivers that usually flow from northwest to southeast.

Diagram 13: Installed capacity of hydroelectric plants in the individual regions of Sweden



Source: Own presentation according to [Svensk Energi]

(2) The **total installed capacity** of hydroelectric plants in 2010 added up to approximately 16,700 MW and the net electricity generation was about 69,600 GWh. Sweden is mainly characterised by run-of- river type and hydro-storage plants. The capacity of the pumped-storage hydropower plants is very low at 100 MW and, as in Norway, they are only operated seasonally.

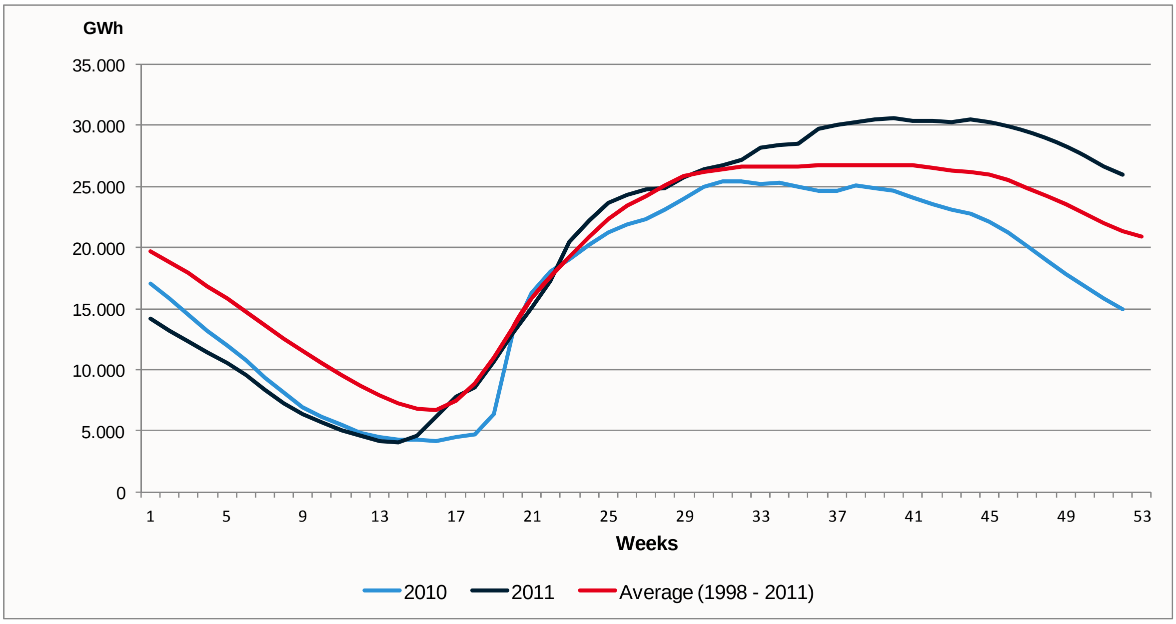
Table 5: Hydro-storage and pumped-storage plants in Sweden in 2010

Type	Capacity [MW]	Generation [GWh]
Hydroelectric power plants	**16,735***	**69,610***
- Hydro storage power plants	10,802	33,700**
- Pumped hydro storage	108*	
- Run-of-river power plants	5,825**	

*Sources: * [Eurostat], **[SINTEF]*

(3) The maximum working volume of the Swedish reservoirs is 33.8 TWh. Diagram 14 gives a graphical depiction of the **filling level of the reservoirs** in Sweden over several years. It shows a similar trend as in Norway with a low filling level in April and a high filling level in September/October. On average between 1998 and 2011, the lowest filling level was about 6.7 TWh and the highest around 26.8 TWh.

Diagram 14: Filling level of the reservoirs in Sweden, weekly values, in GWh.

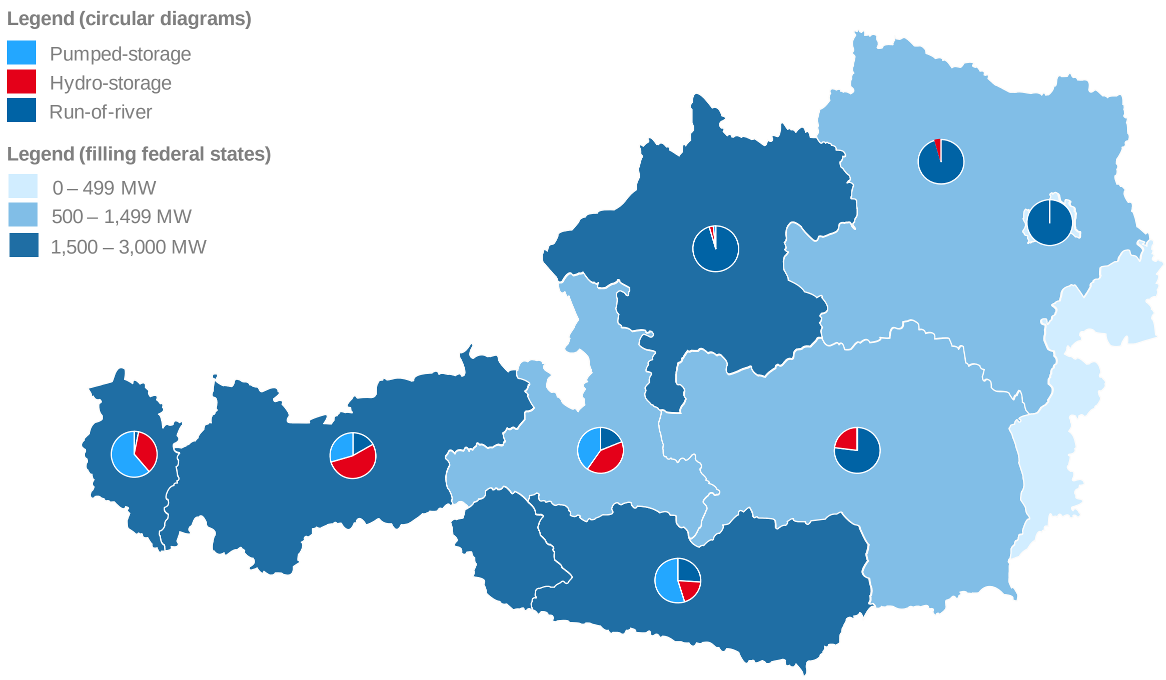


Source: Own presentation according to [Nord Pool Spot8, [Svensk Energi]

4.4 Austria

(1) The electricity generation from hydroelectricity in Austria focuses primarily on **run-of-river type hydroelectric plants** in the river valleys of the Danube, as well as smaller rivers such as the Inn, Salzach and the Mur and the **hydro-storage type plants** in the Alps (see Diagram 15). Austria currently has a number of **pumped-storage hydroelectric plants** and additionally some pure storage-type hydroelectric plants. The electricity generation from storage-type hydroelectric plants (pumped-storage hydroelectric plants and pure storage-type hydroelectricity) in the 2010 calendar year added up to 13.1 TWh. This means that about a third of the hydroelectric generating production was carried out by storage-type hydroelectric plants [E-Control, 2012].

Diagram 15: Hydroelectric plants in Austria



Source: [E-Control, 2012] and hydroelectric-plant-specific data from various electricity suppliers (see bibliography)

(2) The installed turbine capacity in storage and pumped-storage hydroelectric plants in Austria in 2011 registered 7.5 GW (pumped-storage hydroelectric installations: 3.8 GW, hydro-storage plants: 3.7 GW). The share of storage type hydroelectric plants in the installed capacity of hydroelectric plants is 58% [E-Control, 2012]. Sources from various electricity supplying companies confirm that new building programmes in the field of pumped-storage hydroelectric plants are planned up to 2020 amounting to approximately 1.9 GW in volume. In the process the majority of ex-

isting storage capacities will be equipped with new pumps and turbines.

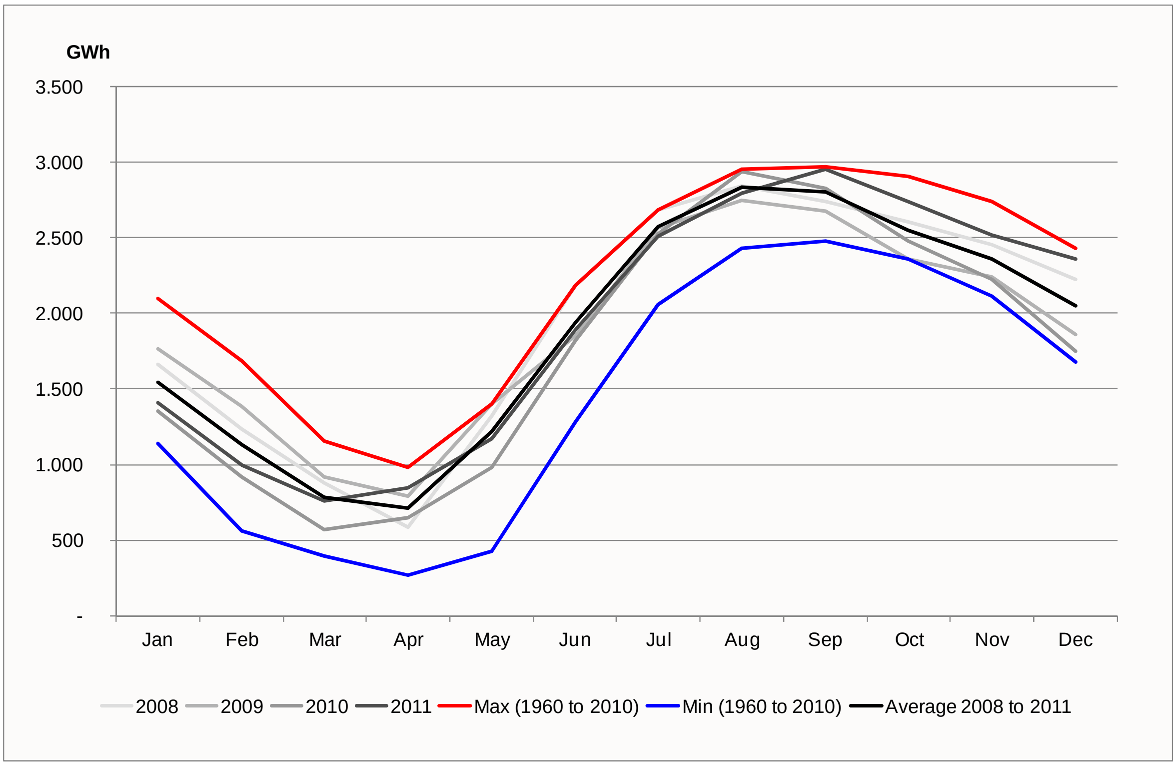
Table 6: Capacity and performance specifications of the storage and pumped-storage hydropower plants in Austria

Type	Number	Turbine capacity [MW]	Expected generation p.a. [GWh]
Hydro-storage power plants	95	3,744	7,824
Pumped-storage	16	3,781	rd. 5,300*
Total hydro storage	**111**	**7,524**	**13,117**
Planned pumped storage (until 2020)	6	1,900	rd. 2,700**

Source: [E-Control, 2012] and hydroelectric-plant-specific data from various electricity suppliers (see bibliography)
(*) calculated values, (**) calculated future production expectations

(3) The **hydroelectricity generation** from storage-type hydroelectric plants depends on the inflow into the reservoirs and equally so on water availability. Different hydrological conditions in different years have as a consequence that in comparison to other years fluctuating monthly filling levels of the storage lakes (see Diagram 16) occur. For example, low rainfall summers cause lower filling levels in the storage lakes in the winter months and therefore fewer opportunities for electricity production in this period. At the same time, demand for electricity is higher in winter and is partially covered by storage-type hydroelectric installations. The filling level minimum (and hence a possible restriction of electricity production from storage-type hydroelectric plants) is reached in April. In Austria, after a comparison over many years, a difference in the storage filling levels of 800 GWh has been registered [E-Control, 2012].

Diagram 16: Filling level of the storage type hydroelectric plants in Austria, monthly values, in GWh



Source: [E-Control, 2012]

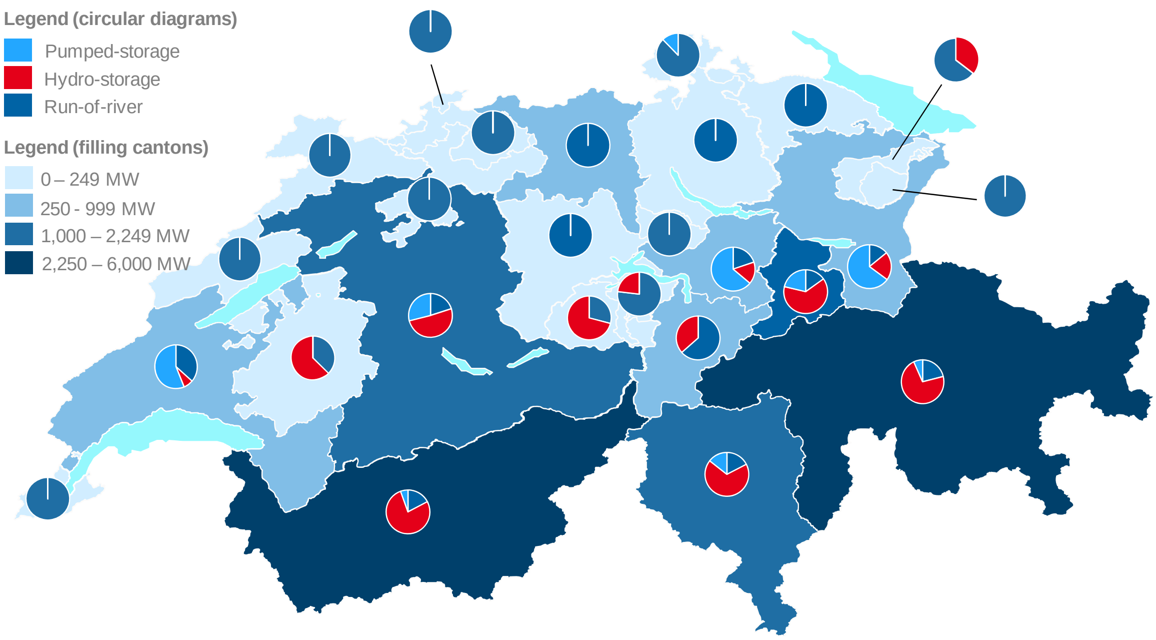
(4) **Pumped-storage plants** in Austria are currently mainly used for electricity storage and generation over relatively short periods of time. This means that at times of low demand (e.g. at night) energy gets stored in the upper reservoir and released at times of high demand (e.g. peak demands within one day). For storage of energy over a longer period, the restrictions inherent to the storage capacities of the upper and/or lower reservoirs have to be taken into account.

4.5 Switzerland

(1) On a long-term average, the generation from hydro-storage plants (pumped-storage hydroelectric plants and conventional hydro-storage plants) in **Switzerland** amounts to about 19.8 TWh (calculated value on the basis of [BFE, 2011 b]). As a consequence, a little more than half of the hydroelectricity generation is accomplished through hydro-storage plants. These types of installations provide in Switzerland practically the entire dispatchable generation. The geographical allocation of hydroelectric plants is determined by the topographic structure of Switzerland. Storage and pumped-storage hydroelectric plants are mainly located in the

central Alps, while much of the run-of- river type hydroelectric plants are to be found in the less mountainous cantons north of the Alpine divide.

Diagram 17: Hydroelectric plants in Switzerland



Source: Own presentation according to [BFE, 2011b]

(2) The **installed turbine capacity** in storage and pumped-storage hydroelectric plants in Switzerland in 2011 registered 9.9 GW (pumped-storage hydroelectric plants: 1.8 GW, conventional hydro-storage plants: 8.1 GW). Therewith the installed capacity of these power generation technologies lies in the area of the maximum load occurring during the winter in Switzerland. The share that storage-type hydroelectric plants contribute to the installed capacity of the hydroelectric plants is 72% [BFE, 2011b]. Sources from various electricity supplying companies confirm that new building projects in the field of pumped-storage hydroelectric plants are planned up to 2020 amounting to approximately 4.0 GW in volume.

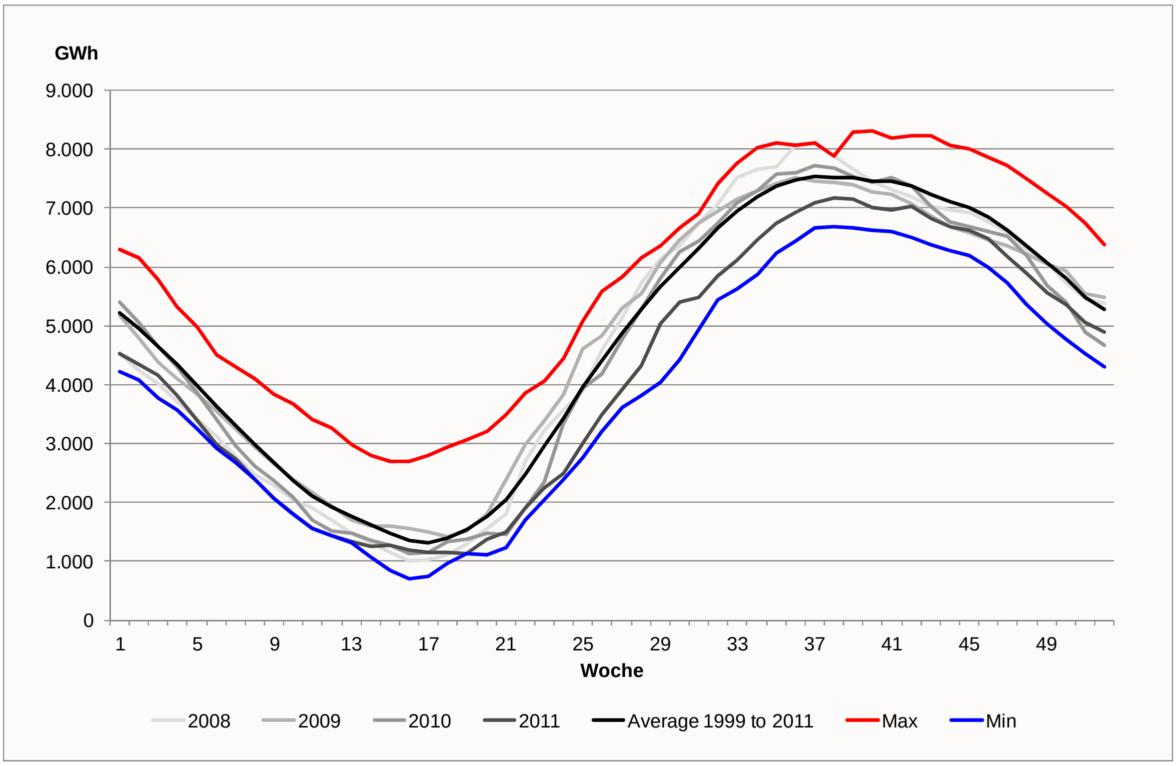
Table 7: Capacity and performance specifications of the storage and pumped-storage hydroelectric plants in Switzerland

Type	Number	Turbine capacity [MW]	Expected generation p.a. [GWh]
Hydro storage power plants	86	8,078	17,286*
Pumped-storage	17	1,839	Rd. 2,500*
Total hydro storage	**103**	**9,918**	**19,791**
Planned pumped storage (until 2020)	6	3,986	rd. 5,600**

Source: [BFE, 2011b]
(*) calculated values, (**) calculated future production expectations

(3) The annual development of the **filling level of storage lakes** shows a similar profile as in Austria. In addition, Diagram 18 shows that the maximum working volume of the storage lakes in Switzerland is significantly higher than in Austria. The minimum filling level (and hence a possible restriction of electricity production from storage-type hydroelectric plants) is reached on average at the end of April. In Switzerland, after a comparison over many years, a difference in the filling levels of up to 2,000 GWh has been established.

Diagram 18: Filling level of storage type hydroelectric plants in Switzerland, monthly values, in GWh



Source: [BFE, 2011a]

(4) **Pumped-storage hydroelectric plants** as in Austria are currently used for electricity storage and generation over relatively short periods. For a possible storage of energy over longer periods, the restrictions inherent to the storage capacities of the upper and/or lower reservoirs have also to be taken into account in Switzerland.

(5) For a **future contribution** of storage and pumped-storage hydroelectric plants in Switzerland to make electricity storage and generation available at European level, the development of the Swiss electricity generation must also be taken into account. The future of the Swiss electricity supply will be discussed anew after the Federal Council's decision on the gradual phasing out of nuclear energy [UVEK, 2011]. A future electricity generating structure, which is characterised by a high proportion of photovoltaic installations, requires a greater demand for the utilisation of storage and pumped-storage hydroelectric plants in the long term within Switzerland as well [compare the excursus in Prognos, 2011]. The same reasoning can also be applied to the development of power generation in Austria and the Austrian storage-type hydroelectric plants.

Restrictions need also to be considered during the use of the **potential in the Alpine region** by a third party, even under a future expansion of pumped-storage hydroelectric plants. This does not contradict an intensification of the electricity connections between the surveyed countries since the dispatchable capacities of the Alpine region, especially in the short and medium term, can make an important contribution to the integration of renewable generation, especially of the generation from photovoltaic facilities in southern Germany. The storage of generated electricity from the north German wind energy is still hampered in a north-south direction across the German interior by the lacking of transmission capacities.

4.6 Summarised assessment

(1) In summary, the following Table 8 presents the previously listed characteristics of the hydroelectric installations of each individual country in alphabetical order. Compared with each other, it becomes clear that Norway, in particular, has a high capacity at its disposal, followed by Sweden. This is also reflected in the electricity generating production.

Table 8: Characteristics of the hydroelectric plants in the countries surveyed

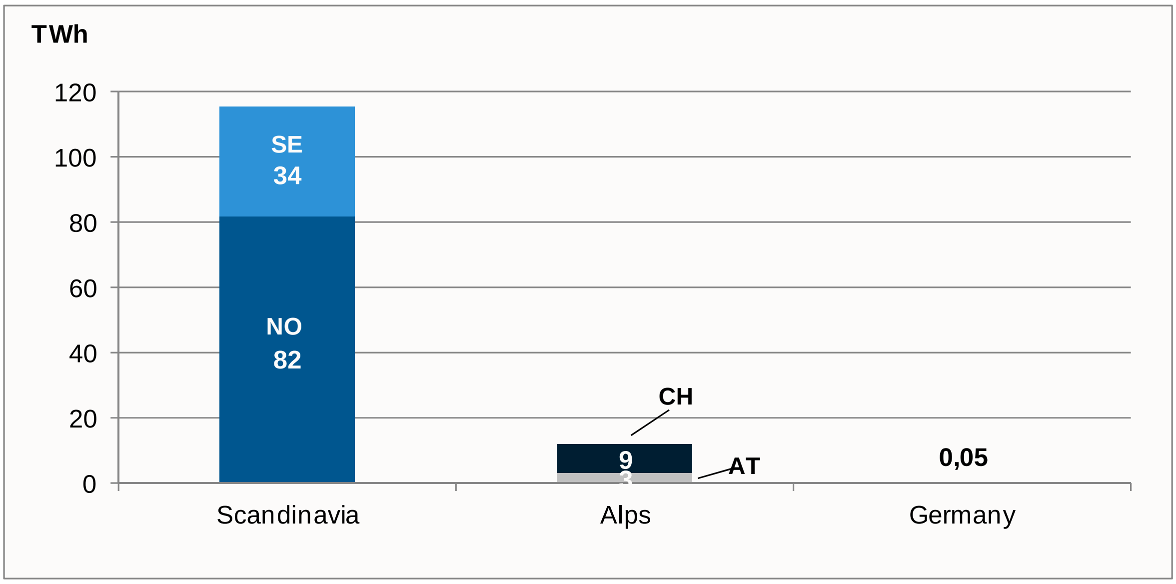
	AT	CH	DE	NO	SE
Capacity of hydroelectric power plants [MW]	**12,919**	**13,728**	**9,790**	**31,004**	**16,735**
- Hydro storage power plants	3,744	8,078	335	23,405	10,802
- Pumped-storage	3,781	1,839	6,521	1,344	108
- Run-of-river power plants	5,395	3,810	2,934	6,255	5,825
Power generation from hydroelectric power plants [TWh]	**39.9**	**37.5**	**23.25**	**116.95**	**66.38**
Full load hours [h]	3,088	2,728	2,375	3,772	3,967

Source: [BDEW 2009], [BFE], [Destatis], [E-Control], [Eurostat], [SINTEF] and data of electricity generating plants by electricity providers

(2) These conditions are furthermore also particularly evident when looking at the maximum storage capacity (see Diagram 19). Today's storage capacity in Scandinavia (NE and SE) exceeds

with about 116 TWh the German capacity (about 0.05 TWh[5]) by nearly the factor 2.300 and those from the Alpine region (Switzerland and Austria) with approximately 12 TWh by the factor 10. Accordingly, in the long term, interconnectors to Scandinavia to accommodate excess electricity and to cover the reserve capacity in Germany become all the more attractive.

Diagram 19: Maximum storage capacity in Norway, Sweden, Austria, Switzerland and Germany in 2011, in TWh



Source: [Nord Pool Spot], [E-Control 2012], [BFE 2011a], [SRU 2011], estimates by Prognos AG

(3) In addition, the potential to construct new hydroelectric plants remains a possibility in these countries. The different data bases prevent the countries from reaching a comparable capability with each other for the construction of new hydroelectric plants. In general, theoretical, technical, ecological, economic, exhaustible and estimated potentials can be distinguished from country to country (see Appendix,

[5] Source for the capacity of pumped-storage hydroelectric plants is [SRU 2011]. The capacity of the storage type hydroelectric plants was taken from Prognos estimates.

Table 12). The technical potential to construct extensions to hydroelectric installations in Germany is, in comparison to the other countries, low and lies between 4.6 to 5.2 TWh [BMU 2010]. In Austria, there is a techno-economic potential of 17.9 TWh [Pöyry 2008] and in Switzerland an expected potential for hydroelectric installations, excluding pumped-storage installations, of between 1.5 to 3.2 TWh [BFE 2012]. In Sweden, the economic potential is about 25 TWh [WEC] and in Norway the expected potential lies at 33.8 TWh [NVE 2011b]. The literary sources provide no information regarding capacities associated with these working volumes. The intensification of water conservation, depending on the circumstances, could further restrict additional useful potentials.

The sketchy data situation, when reference is to potentials, is not an obstacle to the investigative issues underpinning the nature of this study. On the contrary, the analysis of the available (storage facilitated) hydroelectric plants has already underlined the considerable potential of electrical energy storage. Parts of future generation surpluses could be absorbed by combining electricity systems, consisting of predominantly volatile power generation with hydroelectricity-based power systems through interconnectors. At the same time, the development of new water storage facilities in these countries is not necessary as a first step.

5 Transmission capacities between the surveyed countries - status quo and prospects

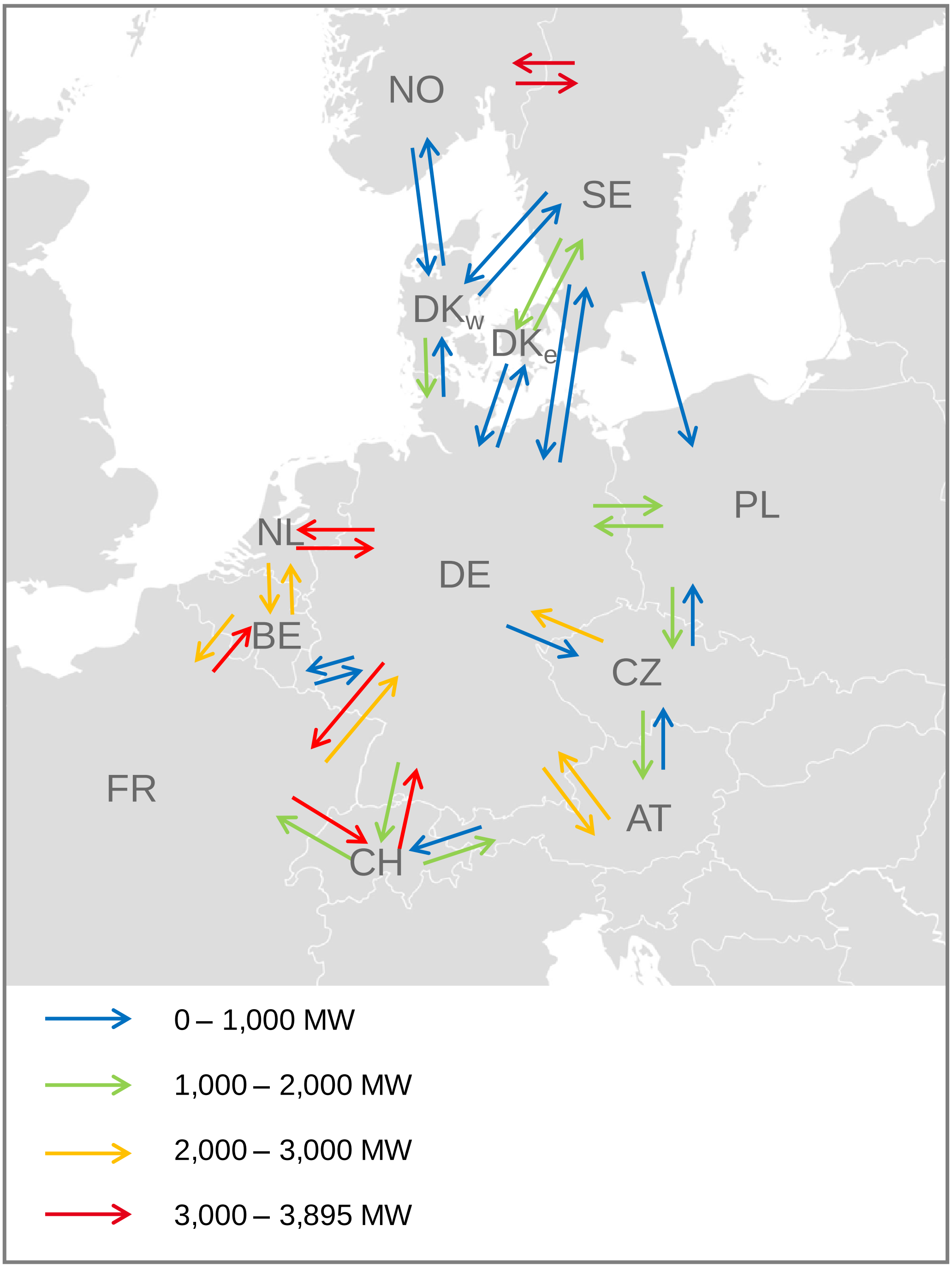
(1) Today, already many **connections** between Germany and its neighbouring countries are in place. The value norm for the existing capacity between countries is the so-called net transfer capacity (NTC, German: "Nettoübertragungskapazität"). The NTC is the expected maximum capacity that can be transported via the connecting lines between two systems, taking into consideration some uncertainties of the transmission system without creating congestion in either system. Due to the different load situations, the ENTSO-E establishes the NTC for a typical load flow situation, namely one for the summer and one for the winter. Hence, Denmark is considered in the process as being divided into Denmark East and Denmark West.

(2) **Diagram 20** shows in megawatts the net transfer capacities of Germany and the neighbouring countries in winter 2010/2011.. The highest net transmission capacity among the selected countries occurred from Sweden to Norway with 3895 MW.

(3) Considering the NTC between Norway/Sweden and Germany, also **Denmark** should be included. Because of the cross-border cable, the "Baltic Cable" between Sweden and Germany, the NTC of around 600 MW existed. From Sweden to Denmark East 1,300 MW and from Denmark East to Germany 585 MW could be transferred. In the opposite direction, the NTC between Germany and Denmark East amounted to 600 MW and between Denmark East and Sweden 1,700 MW. In addition to the net transfer capacities from Sweden to Denmark East, there existed another to Denmark West of 680 MW. In the opposite direction it amounted to 740 MW. The NTC from Denmark West to Germany amounted to 1,500 MW and in the opposite direction to 950 MW. Norway has no direct connection to Germany at its disposal and therefore also no direct transmission capacity. However, Norway is connected via the Skagerrak cables with Denmark West. Thus, in the winter of 2010/2011 the net transfer capacity between Norway and Denmark was 950 MW in both directions.

(4) Cross-border connections exist between Switzerland, Austria and Germany , which make a direct electricity exchange possible. The NTC from Austria to Germany in the winter of 2010/2011 measured 2,000 MW and 2,200 MW in the opposite direction. From Switzerland to Germany, the net transfer capacity stood at 3,500 MW, with 1,500 MW in the opposite direction.

Diagram 20: *Net transfer capacities (NTC) in the winter of 2010/2011*



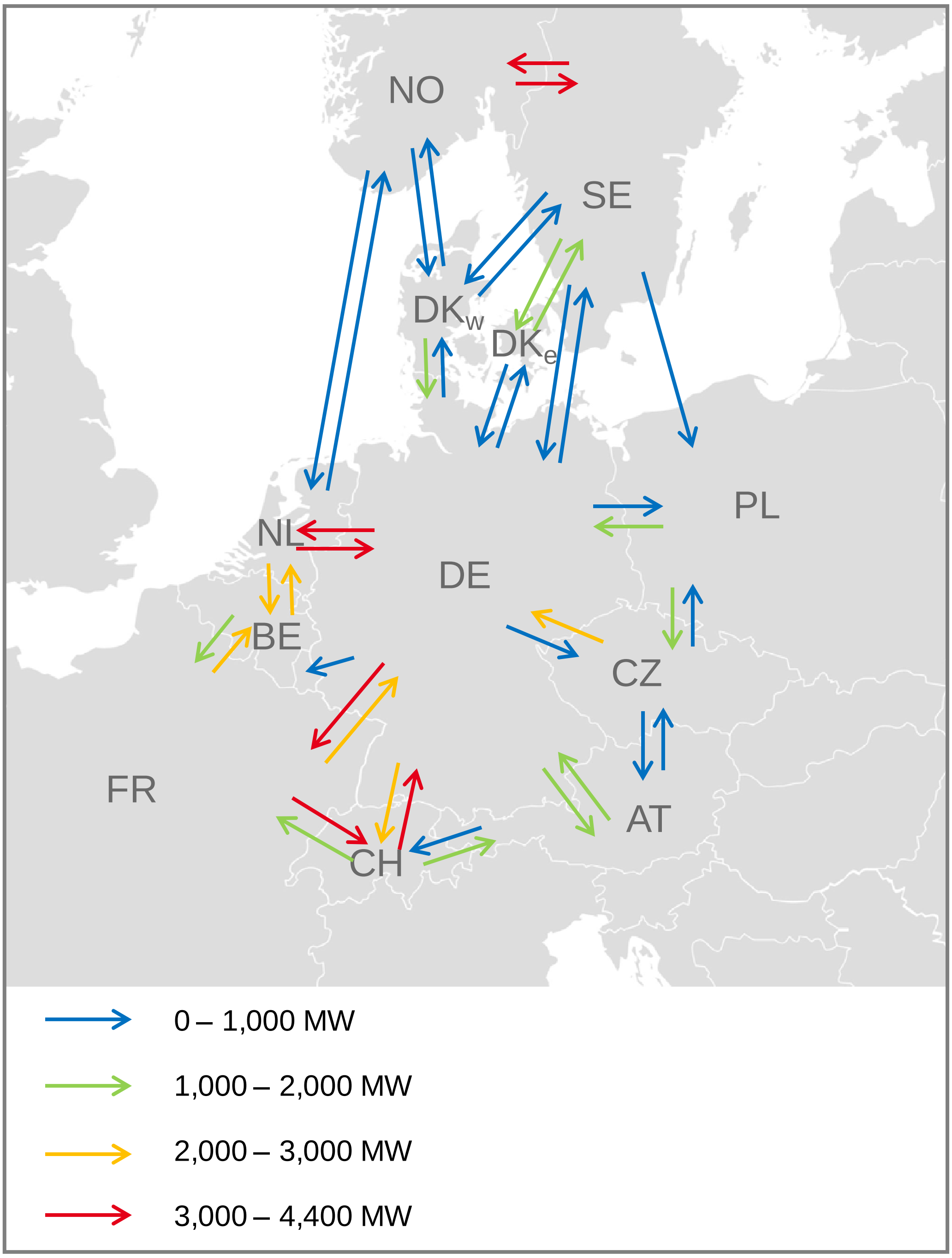
Source: Own presentation according to [ENTSO-E a]

(5) **Diagram 21** presents graphically the net transfer capacities of Germany and its neighbouring countries in the **summer of 2010** in megawatts. In this observation, the highest NTC existed from Switzerland to Germany consisting of 4,400 MW and 2,060 MW in

the opposite direction. The net transfer capacities from **Austria** to Germany amounted to 1,600 MW in both directions.

(6) The net transfer capacities from **Sweden** to Germany amounted to 600 MW in both directions. From Sweden to Denmark East 1,300 MW and from **Denmark East** to Germany 550 MW could be transferred. In the opposite direction, the NTC between Germany and Denmark East amounted to 550 MW and 1,700 MW between Denmark East and Sweden. In addition to the net transfer capacities from Sweden to Denmark East, there existed capacities to Denmark West of 340 MW. In the opposite direction it amounted to 370 MW. The NTC from Denmark West to Germany amounted to 1,500 MW and in the opposite direction to 950 MW. Between Norway and Denmark West the net transfer capacity was 950 MW in both directions.

Diagram 21: Net transfer capacities in the summer of 2010

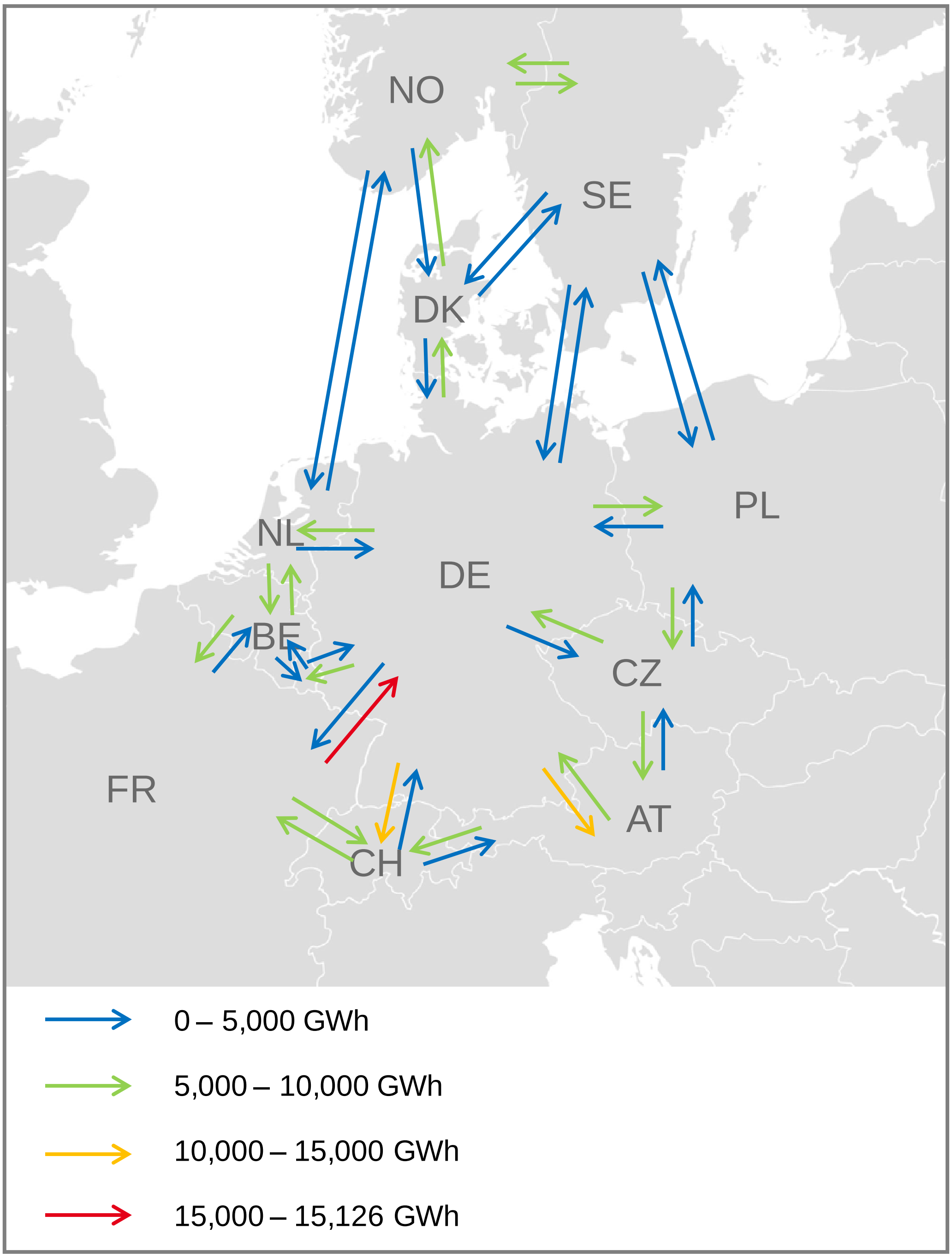


Source: Own presentation according to [ENTSO-E a]

(7) Closely associated with the net transfer capacities is the **electricity exchange** (exports and/or imports) between the countries. Diagram 22 gives a graphic presentation of Germany's cross-border electricity exchange in 2010 with neighbouring countries in gigawatt hours. Also in this year, France exported the most electricity to Germany with approximately 15,100 GWh, followed by the

export from Germany to Austria with around 14,700 GWh and to Switzerland with about 14,600 GWh.

Diagram 22: Electricity exchange in 2010

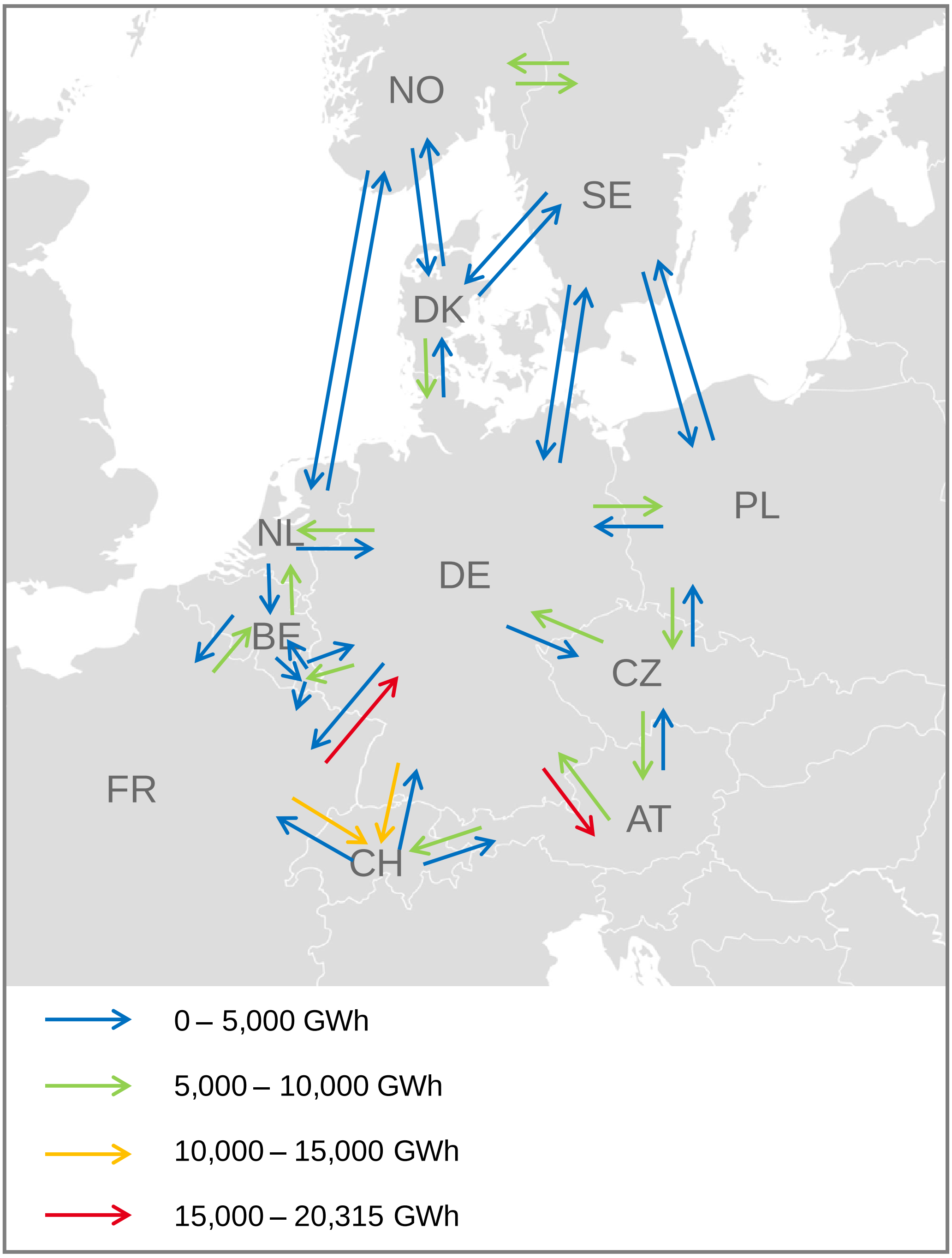


Source: Own presentation according to [ENTSO-E a]

(8) Diagram 23 shows Germany's **cross-border exchange of electricity** with neighbouring countries in gigawatt hours for 2011. France exported the most electricity to Germany with approximately 20,300 GWh, followed by the export from Germany to Aus-

tria with around 15,900 GWh and to Switzerland with about 14,000 GWh.

Diagram 23: Electricity exchange in 2011[6]



Source: Own presentation according to [ENTSO-E a]

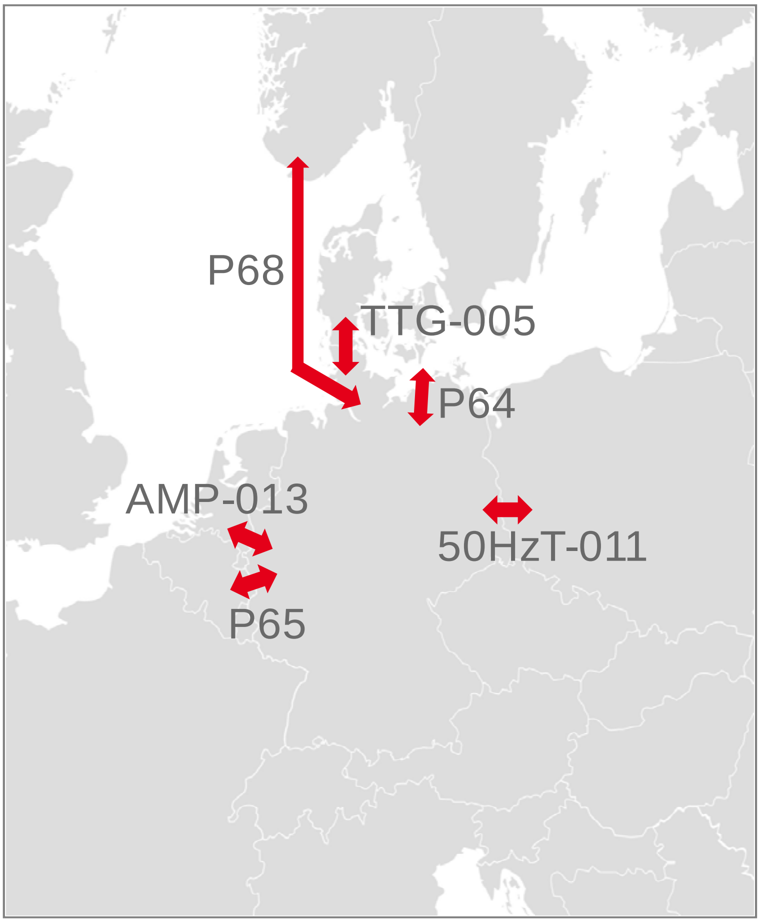
[6] Note on different method of calculation, in contrast to 2012: some information is already flow-based with regard to the launch of the Single European Energy Market in 2014.

(9) In addition to the existing cross-border connections, **more connections** are being planned due to the implementation of the single European Electricity Market. On the one hand, projects can either be taken from the second draft of the German electricity network development plan 2012 of the German Transmission System Operators (TSO) ["Netzentwicklungsplan Strom" - NEP 2010] or, on the other hand, the Ten-Year Network Development Plan 2012 of ENTSO-E [ENTSO-Ec].

(10) The following Diagram 24 shows the **planned interconnectors** of the second draft of the Electricity Network Development Plan 2012. There are five projects, three of which are allocated to the starting grid [7] and two to the resultant grid, which to a certain extent presents a chronological order (for the exact definition of these terms see [NEP 2012]). One of the projects is an interconnector called NORD.LINK (P68) between Norway and Germany, which will connect the two countries with a capacity of around 1,400 MW. Moreover, the connection (TTG-005) between Denmark and Germany will be extended from the voltage level of 220 kV to 380 kV. The joint project of 50 Hertz and the Danish transmission system operator Energinet.dk (P64) is furthermore to connect Denmark and Germany through an interconnector between the offshore wind farms Baltic 2 and Kriegers Flak 3. The following Table 9 gives a detailed list of the depicted projects.

[7] For a definition see Chapter 3.3

Diagram 24: Planned interconnectors of the second draft of the Electricity Network Development Plan 2012



Source: Own presentation according to [NEP 2012]

Table 9: Planned interconnectors of the second draft of the Electricity Network Development Plan 2012

Nr.	Name	Type
P64	Combined Grid Solution (DK – DE)	New construction
P65	Oberzier (DE) – Belgien	New construction
P68	NORD.LINK (NO – DE)	New construction
50HzT-011	Eisenhüttenstadt – Baczyna (PL)	New construction
AMP-013	Niederrhein (DE) – Wittenhorst (DE) – Grenze (NL)	New construction
TTG-005	Audorf (DE) – Flensburg (DE) – Kassø (DK)	Extension

Source: [NEP 2012]

(11) Also the **Ten-Year Network Development Plan** 2012 (TYNDP) ENTSO-E [ENTSO-E c] lists cross-border projects in the European region. The TYNDP designates medium-term (until 2016) and long-term European network development projects. The projects are listed in this context, namely those that should increase the transmission capacities between Scandinavia and Germany and those between the Alpine countries and Germany.

(12) **Norway** will develop and expand the high-voltage network in the medium and also in the long term. These are mainly national projects up to 2016, as well as the fourth Skagerrak cable between Norway and Denmark with a capacity of about 700 MW. In the long run, the national grid will be expanded, as well as the aforementioned cross-border cable NORD.LINK and NorGer to Germany with a capacity of approximately 1,400 MW. In addition, the network between Norway and Sweden will be reinforced.

(13) The medium-term network development plans of **Sweden** earmark an expansion of the national network to the south. This will reinforce the network near the cross-border Baltic Cable. In the long term, the network will be reinforced to Norway, among others.

(14) Even though **Denmark** is not part of this study, the Danish network development will be considered here in this context. The reason for this is the cross-border Skagerrak cables, which connect Denmark with Norway. In the medium term, as already mentioned in paragraph (12), the fourth Skagerrak cable is being built and furthermore a cable is extended from the landing point of the Skagerrak cables in the direction of Germany. In the long term, the cross-border hub between Denmark and Germany on the east coast will be reinforced as well. This reinforcement is also included in the German Electricity Network Development Plan 2012.

(15) Just a few development projects are planned for **Austria** until 2016. However, among other things, a cable on the border with Germany is to be extended. In the long run, a cable between Germany and Austria will be further expanded and others will be newly constructed near the border. In the medium and long term, the capacity will consequently be increased by more than 2,000 MW.

(16) In **Switzerland** a number of national expansion projects and new constructions are planned for the medium term. Also for the long term, these are planned to be ongoing. A variety of cables are to be extended and newly built in the long-term, especially in the border triangle Germany-Austria-Switzerland. This will increase the transmission capacity of the cables by about 4,000 MW.

(17) **In summary,** it can be stated that several cross-border connections from the German transmission network system already are in existence, however, these are still relatively weak in the direction of Scandinavia. A direct connection to Norway will only come into existence with the planned interconnector NORD.LINK. In most countries activities and planning exist for network reinforcements, both in their interiors, as well as cross border. However, cable projects are of long-term nature and require a considerable planning and implementation timeframe.

6 Storage utilisation options in Scandinavia and the Alpine region

6.1 Verification of the requirements for indirect storage

(1) In terms of a possible utilisation of the storage facilities in Scandinavia and in the Alpine region the following two **questions** need to be answered to begin with:

- Can excess energy from Germany be consumed directly in the partner countries or are pumping operations necessary?
- Can Germany import electricity from the partner countries, even if they themselves have a high load in the electricity network?

When electricity is directly consumed and the storage facilities are spared in the process, the electricity can be imported back at a later point in time (indirect storage). In this way, losses would be avoided during pumping operations.

(2) To answer the first question, the **minimum load capacity** of the countries involved needs to be considered. The following Table 10 presents, on the one hand, the minimum loads of individual countries, as well as the common minimum load for the year 2010. It shows that the total minimum load of the four partner countries in 2010 never fell below 25 GW. Even when the must-run capacities in individual countries were considered, such a significant import capacity could be accommodated, an estimated 14 to 18 GW. Of these, the Alpine region was assigned with 4 to 5 GW and Scandinavia with 10 to 13 GW. In this way, excess energy from Germany could be consumed in the partner countries. We assume that during times of an electricity surplus in Germany that the German electricity prices will be lower than in Scandinavia. This will provide the economic incentive to import from Germany.

Table 10: Minimum load of partner countries and Germany in 2010

	Individual minimum load [MW]	Combined minimum load [MW] (Sunday, 1 August 2010, 06:00 AM)
AT	3,715	3,757
CH	3,258	3,459
SE	8,920	9,246
NO	8,392	8,482
Sum*		**24,944**
DE	34,608	36,341

* The sum of the minimum load is not the common minimum load, because they occur at different times.
Source: [Entso-E a]

(3) The second question prompts the appropriate consideration of the **maximum load capacity** and the reserve capacity (then still available) of the countries. The following Table 11 lists the individual maximum loads of partner countries and Germany, as well as the common maximum load for the year 2010.

The maximum load in **Norway** and **Sweden** amounted to about 49 GW. The maximum load fluctuates from year to year. In 2011 this figure was 48 GW. In contrast, a controllable installed capacity in Sweden and Norway of around 65 GW was registered [according to Statnett and Svenska Kraftnät]. As a first approximation, both countries thus had, at the time of their maximum load, a capacity reserve of just over 16 GW. Due to water-level related limitations involving hydroelectricity, shortages in the transmission network (particularly in the north-south direction), as well as the expected power plant outages, only a capacity reserve of about 6.5 GW is available during a normal winter in Norway and Sweden [Source: Information from Statnett and Svenska Kraftnät].

Through the development of the interconnectors and a supply of surplus electricity to Scandinavia, the available reserve capacity probably will increase in the future, because the filling level and thus the available electricity generating capacity of some hydroelectric installations can purposefully be increased.

A further limitation in the availability of the Scandinavian reserve capacity lies in the network restrictions of the respective countries. Due to the purpose of this investigation, it was not possible to draw on an extensive Europe-wide network model. The cautious initial estimates of this work-approach, however, show that the Scandinavian electricity system could contribute significantly to the absorption of surplus electricity and to cover the residual load in

Germany. As mentioned previously in chapter 3.1, accommodating a capacity of 12 GW could already enable the utilisation of about 50% of Germany's electricity surplus in 2050 - a value, which in the light of the Scandinavian potential, appears to be realistic.

For the **Alpine region,** the reserve capacities taken at the time of maximum load must be considered as clearly lower. Subsequently, it appears to be advantageous to connect the electricity systems of Germany and Scandinavia as previously planned and thereby to increase the security of supply in Germany and Scandinavia. Hydroelectricity could then be exported to Germany, if the existing renewable energy facilities fail to provide enough energy. Conversely, during periods of very high supply from renewable energy sources in Germany, the electricity can be exported to Scandinavia but also to the Alpine countries to be consumed there directly.

Table 11: Maximum capacity of partner countries and Germany in 2010

	Individual maximum load [MW]	Combined maximum load [MW] (Wednesday, 1 December 2010, 06:00 PM)
AT	9,646	9,444
CH	8,694	8,466
SE	26,713	26,296
NO	23,994	22,543
DE	79,884	79,884
Sum*		**146,633**
NO and SE		**49,886**

* The sum of the individual minimum load is not the common maximum load, because they occur at different times.
Source: [Entso-E a]

6.2 Economic potential for electricity exchange between the partner countries and Germany

(1) The construction of additional interconnectors between Germany and the surveyed partner countries is only then economical from a business perspective if the revenue from operating the interconnectors exceeds the costs. In principle, there must be distinguished between regulated and non-regulated interconnectors. Regulated cables will be financed through publicly-controlled network usage charges. Non-regulated cables obtain their **revenues** primarily through the exploitation of electricity price differences in

the two related market areas. The bigger the price differences in each hour are, the higher the revenues from electricity trading for the operator of the interconnector. The same efficiency analysis should be in place for regulated cables as for the non-regulated, from a macroeconomic point of view.

The **cost** of an interconnector is determined at about 90% of the investment cost, plus costs for the maintenance and operation, as well as costs from transport losses.

(2) The better integration of **Switzerland** and **Austria** is expected to be more profitable in comparison to the cable expansion to **Scandinavia,** because of the shorter distance for each cable project. Moreover, the cost-effective principle is in place to increase the transmission capacity of existing cables and cross-border hubs. In this way the storage and pumped-storage hydroelectric installations in Austria and Switzerland can contribute towards the provision of an operating-reserve conform capacity abroad, insofar as this is permitted by Germany's (still) existing internal network restrictions. This applies in particular to the **medium term** (up to about 2020) by taking the planned projects for pumped-storage hydroelectric installations into consideration.

At the same time, the full potential for the utilisation of hydroelectricity with regard to the capacity (see chapter 6.2) and the work (see Diagram 19) in the Alpine region is much smaller than in Scandinavia. This potential is also utilised by the countries themselves and due to the more central location in Europe, also increasingly more so by the surrounding states (including Italy, France, the Czech Republic, Slovakia and Hungary).

It is foreseeable therefore, from the German point of view, that the meaningful utilisation of the hydroelectricity potentials, which still exist in the Alpine region, requires only a network expansion of a few GW.

In the following paragraphs, the discussion will focus on the possible expansion of capacities between Germany and **Scandinavia,** and thus of a **long-term** problem-solving approach towards the integration of renewable energy sources.

(3) In order to use additional interconnectors optimally, the expansion of the **downstream electricity networks** in Germany and Scandinavia is necessary since these are not yet capable to accommodate essential capacity at any point in time. In Germany and to some extent also in Scandinavia, the networks must already be developed for the transfer of increasing renewable electricity generation. The level of additional expansion necessity caused by

the interconnectors cannot be answered in the context of this study.

(4) The **economic efficiency, i.e. cost** of a **typical interconnector** between Germany and Scandinavia (Norway or Sweden) can be estimated as follows:

- The planned capital expenditure, i.e. investment, for the 645 km long link NORD.LINK connection with a transmission capacity of 1,400 MW amounts to about 2 billion EUR. The cost of further cable projects is expected to lie in the same range. With the usual interest expectation for the energy industry of 8% per year and a calculation period of 20 years, the cable operations must then achieve a surplus of about 200 million EUR annually.

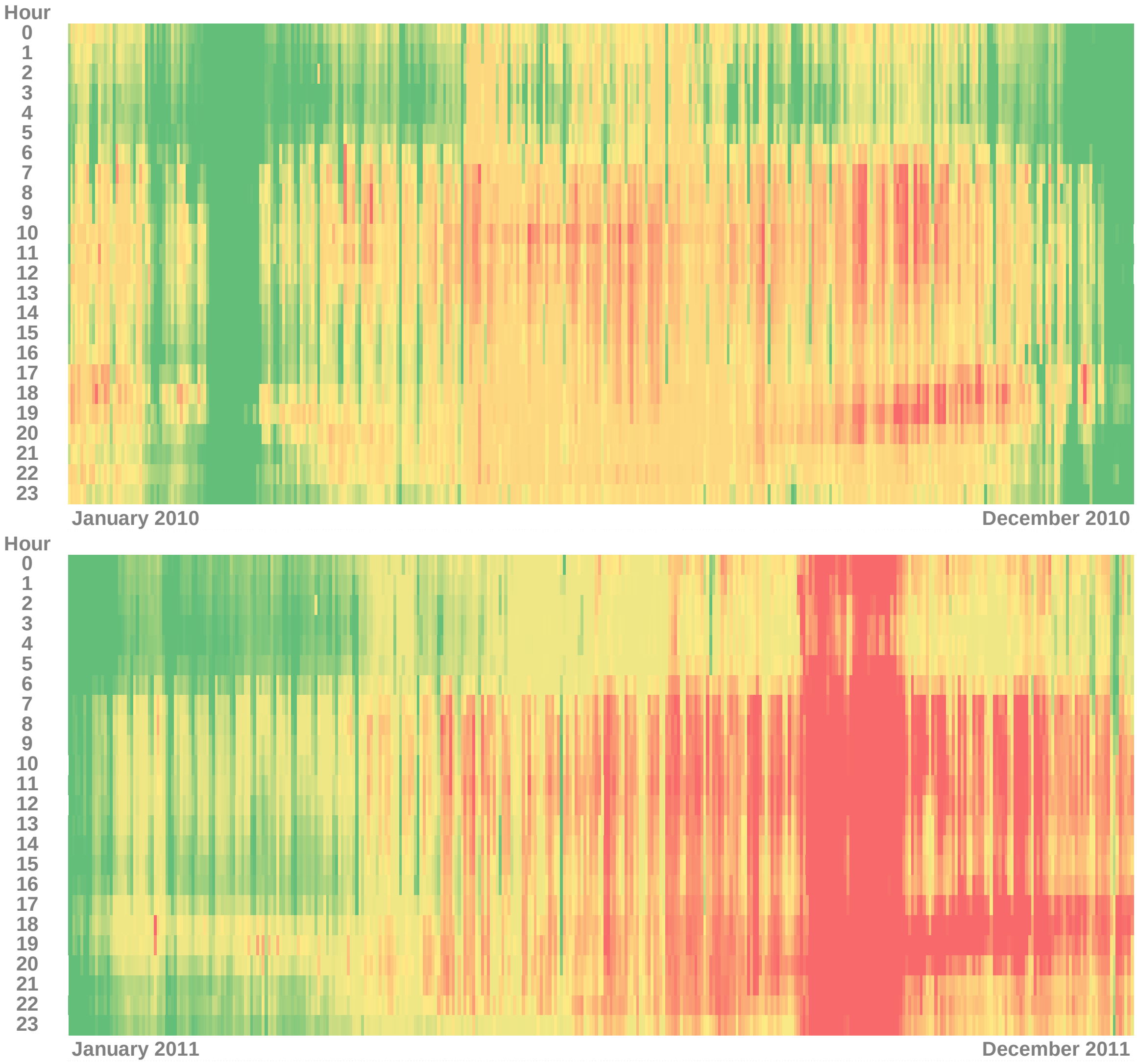
- If the interconnector can be operated throughout the year, revenue per transported MWh of electricity (the price difference between EEX and the Nord Pool market) will be required of approximately 16 EUR. Taking network losses into account, this amount rises to about 18 EUR.

(5) In the years 2010 and 2011, the average/middle **price difference** between the two market areas was slightly below the level that is required for new investments, namely at 13 to 15 EUR/MWh. The following illustration shows the electricity price differences between the Scandinavian Nord Pool (here NO2) and the EEX market. The impact of hydroelectricity on prices in Scandinavia, i.e. the price differences compared with the EEX market, becomes quite clear here. In 2010, low rainfall and a drop in glacier melting led to a below-average electricity production by the hydroelectric installations. The annual mean for the Scandinavian market was more expensive at 9 EUR per MWh than the EEX market. During the months of February, March and December, the differences were even significantly larger.

The low storage filling levels towards the end of 2010 and beginning of 2011 pushed the electricity prices up a lot in Scandinavia. . Due to very heavy rainfall and above-average meltwater, the storage-reservoir levels rose again very sharply in May and June 2011. From May 2011 prices fell in Scandinavia during the peak load times below the price levels of the EEX. Due to more heavy rains in autumn, the storage filling levels rose to such an extent that Scandinavia exported electricity almost all day long in October to Germany, also during the favourable off-peak hours in Germany. On average, the prices on the Nord Pool market area in 2011 were lower by 4 EUR per MWh than those of the EEX market.

Today the existing interconnectors already make a contribution during low storage filling level situations towards system stabilisation and avoid excess electricity during times of very high hydroelectricity production.

Diagram 25: Hourly price differences between Norway (Oslo) and Germany for the years 2010 and 2011



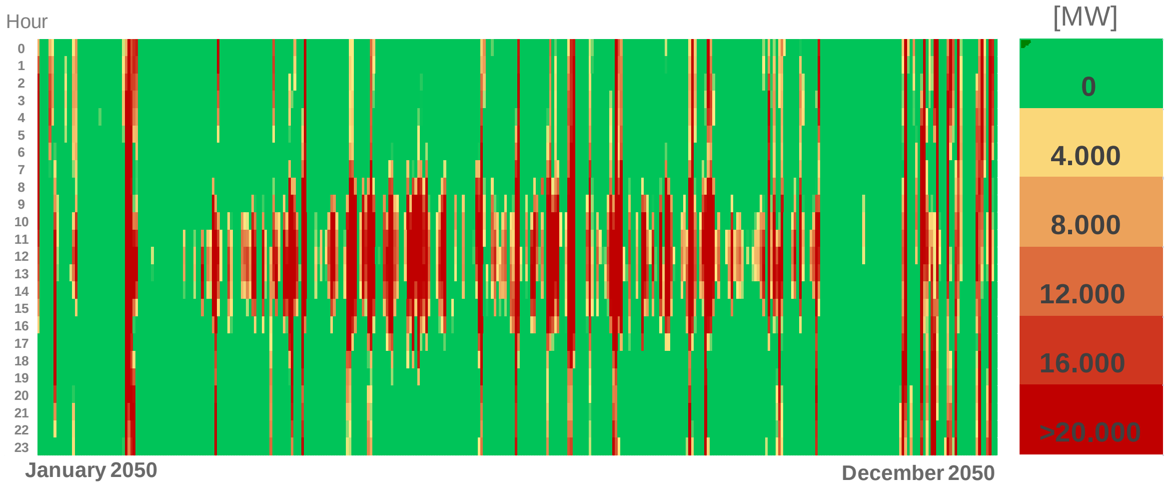
Key: green: EEX at least 10 EUR/MWh cheaper than Norway, red: EEX at least 10 EUR/MWh cheaper than Norway

Source: Own presentation according to [Nord Pool Spot] and [EEX]

(6) In the past, the **availability of hydroelectricity** in Sweden and Norway mainly determined the price differences between the Nord Pool and the EEX markets, now, in the future the growing renewable supply in Germany will become increasingly important.

During periods with strong winds, the EEX price is expected to fall below that of the Nord Pool price for several hours to a few days at a time, in the same manner during the day on sunny days (see Diagram 26). During periods with low wind and PV supply in Germany, the Scandinavian market in general will be more favourable.

Diagram 26: Surpluses due to fluctuating renewable energy sources in Germany in 2050



Explanation: the x-axis shows the time of year, the y-axis the day time. The colour indicates the surplus height of supply from renewable energy sources.
Source: Own presentation

(7) In the **future,** the hourly electricity price differences between the Nord Pool and the EEX markets, compared to today's levels, are expected to increase due to the development of renewable energy sources.

The amount of the price differences is determined not only by renewable supply, but also by the general price level (base load) and by the price of the most expensive hours on the EEX market.

In addition to the **fuel price development**, also the political decisions on the further development of the European **emissions trading**, as well as the electricity market design in Germany, will exert a very important influence.

The higher the climate protection targets in the emissions trading area are, the stronger the price differences between Nord Pool and EEX will rise, because the electricity prices in Germany react in the medium term much more to the increase of CO_2 prices than to the relatively low CO_2 Nord Pool market. With the increasing share of renewable energy sources in Germany, the CO_2 intensity in the two markets will level up in the long run.

(8) In respect of the future **electricity market design** it is crucial for the profitability of the interconnectors, whether very high price spikes are allowed as scarcity signals, or whether this can be prevented by large capacity reserves.

Due to the still **very uncertain political parameters,** the development of the price differences and thus the number of additional economic interconnectors between Germany and Scandinavia can in the short and medium term not be estimated reliably. Furthermore, price differences between Scandinavia and continental Europe are likely to gradually decline with the linking up of the electricity markets, which will also dampen economic efficiency. In addition, interconnectors to Germany are under competitive pressure with every new connection to be built between Scandinavia and other countries such as the Netherlands or the UK.

(9) Prompted by an observation, in which the **use of electricity surpluses** is placed in the foreground, the **meaningful long-term development of interconnectors** can indeed be estimated:

- The value of indirect or direct stored electricity is likely to correspond to the average electricity price, i.e. the average electricity production costs taken macroeconomically. These will in 2050, according to several studies (e.g. [Prognos 2009] (Model Germany), [DLR 2011]), amount to about 80 to 90 EUR_{2011} per MWh90. The use of electricity surpluses in Germany reduces the operation of conventional power plants in the long term, especially of gas turbines. In addition, it is possible to accomplish the same renewable electricity generation with a reduced expansion of renewable energy sources.

- The value of electricity in oversupply situations is determined by the next best (possible) storage option. Judged from the present perspective, these are power-to-gas-to-power (concerning longer-term surpluses) and power-to-heat applications (concerning short-term surpluses). The production and re-channelling/conversion of methane maximally has an efficiency factor of a third. This means that the actual electricity production costs of about 90 EUR_{2011}/ MWh for this type of storage facility type amount to a maximum value of 30 EUR_{2011}/MWh [8]. If excess electricity is used up directly or used for charging of thermal storage facilities, then this electricity has, by saving on fuel, probably also a value in the order of 30 EUR $_{2011}$/MWh [Prognos 2010].

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[8] With the alternative storage options capital costs are to be financed too. By taking these costs into consideration, the value of the electricity surpluses can be lower.

- The yield from the use of electricity surpluses through interconnectors, compared to the most likely alternative uses, amounts to about 50 to 60 EUR $_{2011}$/MWh.

- The cost of future interconnectors is expected to be approximately 1,400 EUR$_{2011}$/kW (this is equivalent to the current cost estimates for the Nord.Link project)

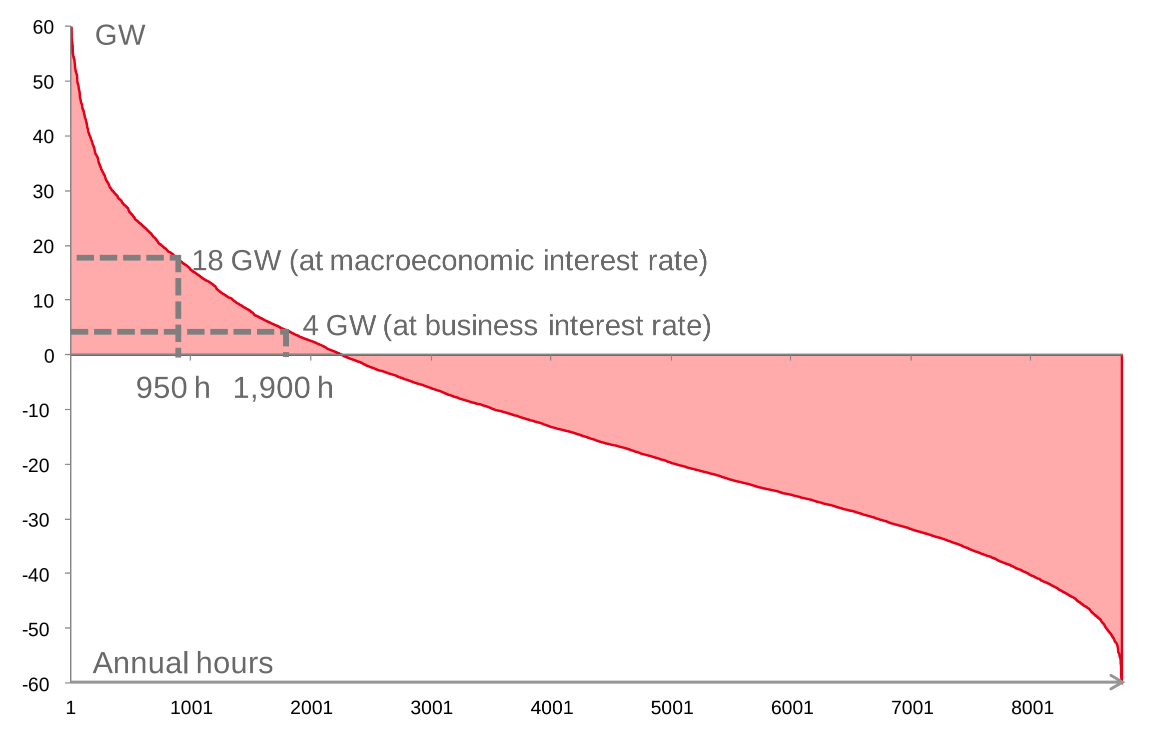
- Due to the stronger connection of markets and capacity reserves in the Scandinavian system, the need for backup capacity in Germany can be reduced. Under the cautious assumption that for every 1,000 MW of additional interconnector capacity 500 MW of backup capacity can be saved, which means in terms of investment costs of 500 EUR$_{2011}$/kW for gas turbine power plants that an additional use of 250 EUR$_{2011}$/kW for future cable projects becomes available. These could be credited if necessary as revenue for the secured capacity. This results in an estimated net cost of 1400 - 250 = 1,150 EUR/kW for the interconnector. In order to materialise this revenue for the operators of the interconnector, an open market design is needed that will allow power supply from abroad, as well as risk-participation by the state, depending on the circumstances..

- The usual interest expectation for the energy industry of 8% per year over a calculation period of 20 years returns an annuity of 10%. The cable operating undertaking must therefore return annual use/benefits of 115 EUR$_{2011}$/kW or 115,000 EUR$_{2011}$/MW. With a revenue of 60 EUR/MWh, the cable must therefore accommodate approximately 115,000 / 60 = approx. 1,900 hours electricity surpluses per year to earn the annuity for the cost of the investment.

- With an economic interest requirement of 4% per year and an observation period of 40 years (annuity of 5%), the annual capital costs for the interconnector decrease to 57,500 EUR$_{2011}$/MW. Considering these assumptions, the construction of additional interconnectors even at a time frame of utilisation (for surplus electricity) of 950 hours per year compared to other storage options would be meaningful.

(10) On the basis of the surpluses on the German electricity market (see following diagram), there arises in the long term an **economic potential** for interconnectors between Germany and Scandinavia of at least about **4 GW** in **business** interest requirements of about **18 GW** at a **macroeconomic** analysis.

Diagram 27: *Economic interconnector capacities when using German surplus electricity in 2050*



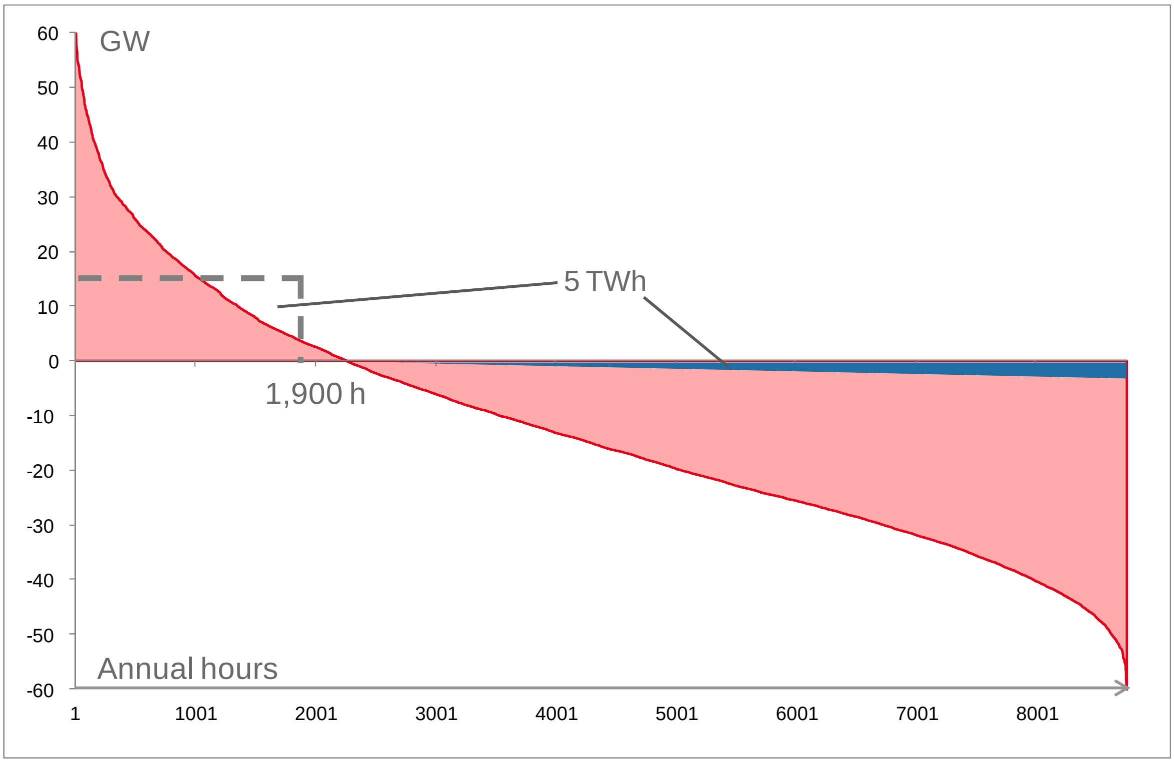
Source: Own presentation

(11) Even in the **partner countries** examined in this study, the renewable energy sources are developed in the longer term. In addition to the development of variable biomass electricity installations (e.g. in Sweden and Austria), a large part of the additional construction work is expected to occur on fluctuating systems such as small hydro, wind and PV in the Alpine region. Therefore the prospect is that also in the partner countries **surplus situations** would arise. For example, an excess of about 20 TWh per year in the future is expected just for Sweden (Source: Information from Svenska Kraftnät).

The greater part of this surplus is not expected to happen simultaneously with the surplus in Germany, because just a few PV systems are to be installed in Scandinavia, while the wind farms in the Baltic Sea, in Sweden and Finland are between 500 to more than 1,000 km away from the German wind farm locations and are therefore exposed to time-delayed greater-weather conditions.

With the utilisation of additional electricity surpluses from Scandinavia, the profitability of interconnectors has **improved** and additional construction is meaningful. Already at an additional utilisation of 2 TWh, the capacity of the interconnectors increases in an economically presentable manner with the adoption of a business-economic rate of return of 4 to **10 GW.** When, in addition to the surpluses occurring in the German market, an additional 5 TWh surplus electricity is used, then in the long term, an electricity connection of **15 GW** between Scandinavia and Germany will be economically (level of business interest expectation) viable.

Diagram 28: Economic performance of interconnectors through the use of German and Scandinavian surplus electricity in 2050 (economic interest request)



Source: Own presentation

Subtracting the already installed performance of 3 GW of today, there emerges a long-term **economic new-construction potential** of **7 to 12 GW** for interconnectors between Germany and Scandinavia.

7 Conclusions

(1) It has been shown that due to the expected increase of renewable energy sources in Germany **surplus situations** will occur in the long term in the German grid, especially in the summer (during the day) and during windy periods throughout the year. On the other hand, even in 2050, renewable energy sources will not be able to meet the entire capacity requirement during the majority of the hours: reserve capacity to cover the residual load is needed. Moreover, the increasing share of renewable energy sources requires additional measures to secure the power supply, e.g. in the area of ancillary services.

(2) The basic **usability of storage facilities** to balance out supply and demand in electricity systems with high components of fluctuating power generation is beyond question. The practical availability of storage facilities in Germany is, however, limited. Today, Germany has primarily pumped-storage installations (6.5 GW). Up to 2020, Germany will have a pumped-storage capacity at its disposal of about 9 GW, which can be used for six to eight hours. The prospect, however, of connecting the German system (with high components of fluctuating power generation) with hydroelectric-based electricity systems via interconnectors contains **significant benefits for both sides.**

- The construction of interconnectors between these power systems makes way for the indirect storage of electricity, especially in Scandinavia due to its significant storage capacity (factor 2,300 compared to Germany). This means that German surplus electricity is consumed in the partner countries, while the local storage facilities there remain closed. In partner countries electricity can then be generated later for delivery to Germany. This is the most efficient method of power storage with an electricity-to-electricity efficiency factor of 90%. An expansion of the hydro-storages for this purpose is not necessary for the time being.

- The interconnectors multiply the electricity exchange between the countries and offer the opportunity for other energy providers to gain access to the respective electricity market.

- For both parties security of supply increases, since the possibilities to prevent congestion are becoming more diverse.

- The Scandinavian system has strengths in guaranteed capacity (MW), because it has a significant reserve capacity at its disposal. In comparison, Germany, however, is likely to have abundant electrical work (MWh) in the future. The combination of these strengths implies economic advantages for both parties.

- Modern interconnectors can provide part of the necessary ancillary services in the environment of their fixed land-entry points (up to about 200 km).

- The economic benefits in the construction of interconnectors materialise when the electricity price differences in the two related market areas are exploited, as well as when the need for essential reserve capacity is reduced.

(3) The long-term use of the Scandinavian storage capacities (116 TWh) and to a lesser extent also the use of storage facilities in the Alpine region (12 TWh) are potential **options** out of **several** to meet the challenges of the German energy transition in the power system. Domestic storage facilities could be built as an additional or alternative option to international storage. Moreover, surplus electricity capacities could be controlled by the production management, if the cost of additional storage or interconnectors would exceed the value of the electricity used. In this case, the back-up reserves will have to be provided by domestic solutions (new gas turbines, existing power plants). It became apparent in this study that the international (indirect) storage of surplus electricity **has advantages over purely domestic solutions.** Electricity surpluses become profitable in business and economic terms if they can be utilised by international storage systems. The pending changes to the design of the electricity market and in the energy markets in general cause immense uncertainty to the economic efficiency of new interconnectors. Price differences between Scandinavia and continental Europe are likely to gradually decline with the coupling of the electricity markets and will also dampen economic viability. Consequently, the benefits of the first interconnectors are the largest. In addition, interconnectors to Germany are under competitive pressure with every new connection to be built between Scandinavia and other countries such as the Netherlands or Great Britain. This argues for a gradual approach in the construction of new interconnectors.

(4) It can be estimated that, based on the evaluation of surpluses from the German and Scandinavian electricity market, an **economic profitability** for interconnectors between Germany and Scandinavia of 10 to 15 GW in an economic rate of return requirement is attainable in the long term. Subtracting the already installed capacity of 3 GW of today, there remains a long-term **economic new-construction potential** of **7 to 12 GW** for interconnectors between Germany and Scandinavia. In order to raise this potential, an open market design is needed that will allow power

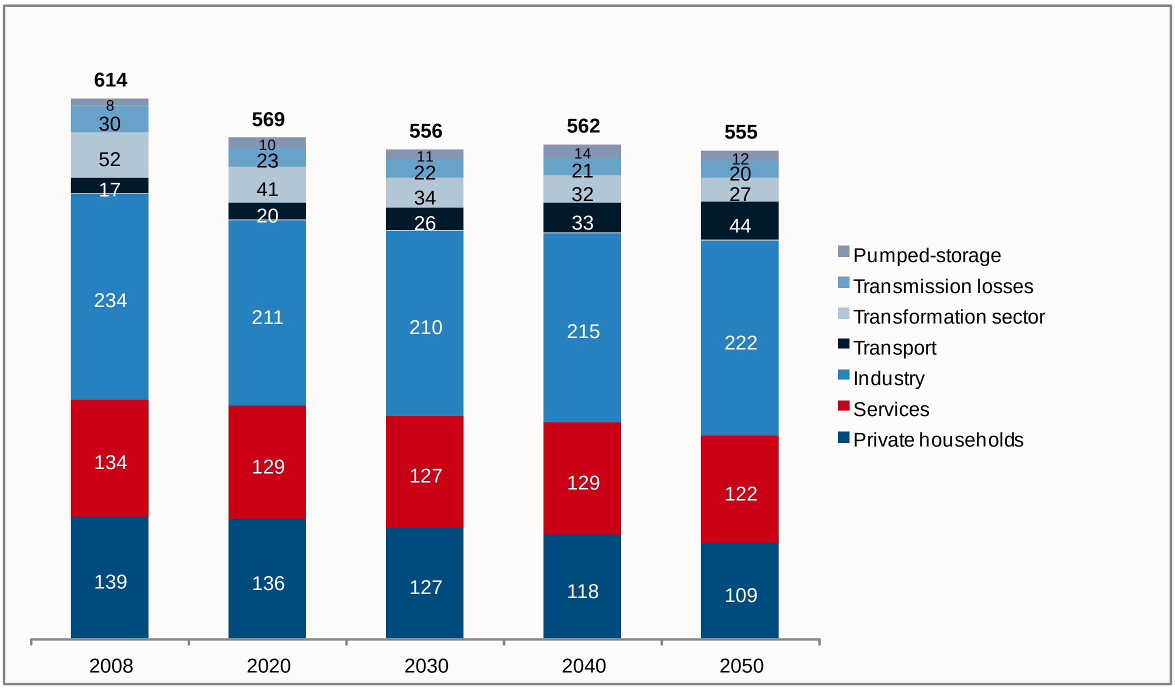
supply from abroad, as well as risk-participation by the state, depending on the circumstances.

In addition to the Skagerrak cable 4 (0.7 GW) already under construction and the planned interconnectors NORD.LINK and NorGer (each with 1.4 GW), more cables with a total capacity between 3.5 and 8.5 GW could subsequently be economical.

(5) In the long run, the indirect storage of excess electricity from renewable energy sources in the Scandinavian hydro-storage power plants can contribute significantly to the German **security of power supply** and the **integration of renewable energy sources**, and in the process, to the energy transition. In the short and medium term, the storage capacities of the Alpine region can already make a contribution albeit to a lesser extent (a few GW).

8 Appendix

Diagram 29: Development of gross electricity consumption in Germany up to 2050



Source: Prognos / EWI / GWS 2010], reference scenario

Table 12: Definitions for hydroelectric potentials

	Description
Theoretical potential	The physically available potential (of an energy source) which can be harnessed in a given region and during a given time period.
Technical potential	The share of a theoretical potential which can be harnessed taking into consideration given technical restrictions.
Ecological potential	The share of a technical potential whose usage does not imply irreversible adverse effects on natural habitats and the interrelation between creatures and their environment.
Economical potential	The share of a technical potential which can be harnessed economically.
Exploitable potential	The intersection between the ecological and the economical potential.
Realisable potential	The share of an exploitable potential which is socially acceptable.

Source: See Die Energieperspektiven 2035 – Volume IV (Excurses) [BFE – Piot, 2007]

Diagram 30: The mechanics of indirect storage

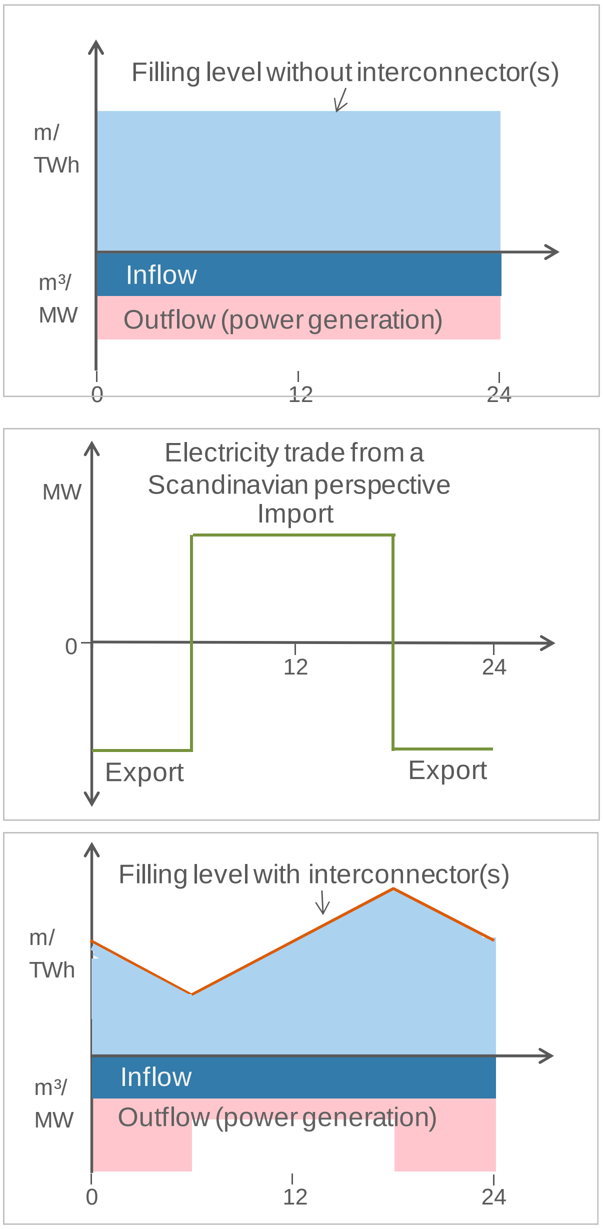


Diagram 30 presents the mechanics of indirect storage in schematic form. The first illustration section indicates the filling level of the reservoir under the assumption that the inflow is equal to the outflow (electricity generation). The second illustration section shows the electricity trade from a Scandinavian point of view: in this example, during the first 6 hours of the day, electricity would be exported from Scandinavia to Germany, from 6 a.m. to 6.p.m electricity is imported and again from 6 p.m. to 12 p.m. exported. This would mean (illustration 3) that during electricity export there is an increased outflow and during import a lower outflow. Accordingly, during the export situation the filling level drops due to higher outflow, during import it increases.

9 Glossary

AT

Country code for Austria

Biomass

In the framework of the Renewable Energy Sources Act (EEG) materials, which are considered to be biomass are defined in the Biomass Ordinance. Under the umbrella term biomass energy sources are understood according to plant or animal origin, as well as their descendant and by-products. From this, solid, liquid and gaseous (biogas) energy sources are won.

Combined heat and power plant (CHP electricity plant)

Modular system for the production of electricity and heat, in which the principle of combined heat and power is used. Usual CHP electricity plant modules have an electricity capacity of between 5 and maximally 10,000 kW.

Gross electricity demand

The total electricity requirement of one year, containing, in addition to the final energy consumption, also the network losses, the own consumption of the power plants and the electricity used in the conversion sector.

Gross electricity generation

Electricity generated supply measured directly at the generator terminal of power plants and other electricity generating installations, usually referring to one reference year.

Cap and Trade

„Limit and act“spearheads the approach by the EU Emissions Trading Scheme (ETS) to control pollution, i.e. the prevention of emissions, at the lowest possible cost. For this purpose, a tight, EU-wide umbrella budget of emission allowances is made tradable ("cap and trade").

CH

Country code for Switzerland

CO_2

Carbon dioxide.

CO_2 equivalents

In order to compare different greenhouse gases (CH_4, N_2O, HFC, PFC, SF_6) corresponding tax-calculation equivalents (CO_2 equivalents) are determined. At the same time, the global warming potential of the other gases is provided in relation to the climatic impact of CO_2. This relationship is expressed by the global warming potential, which was established by the Intergovernmental Panel on Climate Change (IPCC).

DE

Country code for Germany

DK

Country code for Denmark

Electrical net efficiency

The ratio of electricity supply into the grid and the fuel consumption used by the electricity generating installation during optimal operation.

Renewable energy sources / regenerative energies

Identifies energy from sources that are inexhaustible by human standards. These include: solar, biomass, hydroelectricity, wind energy, ambient heat, geothermal and ocean energy.

Renewable Energy Sources Act (EEG)

Act to promote renewable energy sources, i.e. designed to promote the development of energy supply facilities, which are fed from self-renewing (renewable) sources.

Fossil fuels

Fossil fuels are fuels, such as brown coal, hard coal, peat, natural gas and petroleum that originated in the geological past from the decomposed products of dead plants and animals.

Guaranteed capacity

Guaranteed capacity of the installed power plant capacity (rated capacity) is to be distinguish from the secured capacity. The guaranteed capacity of an installation is less than the installed capacity, because the issue of planned and unplanned downtime is taken into account as a discount factor based on the installed capacity. Among the planned downtimes are meant, for example, the shutdown of the installation for maintenance or predictable repairs. Unplanned downtime usually occurs after technical problems, which prevent the continued operation of the plant in the short term. The basis for calculating the guaranteed capacity consists of the statistical analysis of the average annual operational readiness of the various electricity generating facilities.

Gigawatt (GW)

= 1000 megawatts (MW) = 1,000,000 kilowatts (kW), capacity unit of electricity plants

Basic load

The basic or base load describes the capacity load on the network, which is not exceeded in the electricity network during the day. Because the lowest power consumption usually occurs at night, the amount of base load is determined by industrial facilities that produce at night, street lighting and permanent consumers in households and industry. To cover the base load, base-load installations are used with very low electricity production costs, but are variable only at a great expense. They are in operation nearly every day around the clock (6,000 - 8,760 full-load hours) in order to cover the base power supply. If the basic consumption is exceeded, then to cover the additional electrical consumption, medium and peak load electricity installations jump in.

Installed gross capacity

Maximum retrievable electrical capacity with which a power plant can deliver electricity to the grid.

Annual peak load

Designation of the highest simultaneous electricity demand (load) that can occur within a calendar year in an electricity grid. This load must be covered by the available amount of electricity (capacity) of the power plant group. The common unit for the annual peak load in Germany is gigawatt.

Annual efficiency ratio (gross/ net)

This designates the ratio between electricity output of a power plant into the grid together with the fuel consumption in a year. Compared to the annual efficiency (gross), the annual efficiency (net) is adjusted to the power consumption of the power plant.

Capacity

In the description of electricity installations often used as a synonym for performance (secured, i.e. available). The installed capacity of an electricity installation will be the installed capability of the power plant.

Cost-based redispatch

In this instance, in order to balance emerging costs, producers are shut down before congestion occurs, more exactly before the load increases. After a congestion situation exactly the reverse takes place. This procedure is used only in short-term removal of bottlenecks/congestion and is not suitable as a long-term solution, because it creates a lack of transparency about the congestion and creates no incentives for the network operator to resolve congestion. The cost of congestion management is transferred to the network charges of the electricity customers.

Combined heat and power (CHP)

During the CHP operation of an energy conversion installation both the generated heat from both the chemical and the physical conversion of energy sources, as well as the generated electrical energy through the energy conversion are utilised to a large extent. Through the use of waste heat, the efficiency of power plants increases significantly.

Short-term marginal costs

Costs that are incurred for the production of the next unit of a desired product.

Electrical capacity

The installed electrical capacity (el) is the unit/measure for the electrical capacity production in the electricity generating installation indicated in watts (W). When this capacity is retrieved for a period of time, then the installation generates electricity (unit: Wh). The usual unit denominations/ sizes for this kind of performance are kilowatts (kW) or megawatts (MW). The generated electricity in one hour (h) at a capacity/ performance of 1 kW amounts to a kilowatt hour (kWh).

Thermal capacity

Thermal capacity/ power (th), or thermal performance, provides information about the heat generating capacity installed in an installation/ power plant. As with electricity capacity, this is also indicated in watts (W).

Merit order

The set order/sequence of power plants according to their short-term marginal costs.

Medium (capacity) load

The medium load range denotes the range of the daily load curve, in which additional electricity is consumed above that of the base load. The additional power consumption can be covered by medium-load power plants. They are easier to control than base-load power plants. The facilities/ plants are thus operated at times of increased electricity demand, with their full-capacity-load range between 2,000 and 6,000 hours per year. If their capacity delivering performance is no longer sufficient, then peak-load power plants kick in to cover this short-term energy shortfall.

National Allocation Plans

National Allocation Plans distribute to the EU Member States their allocated CO_2 emission allowances if they are participating in the EU Emissions Trading Scheme (ETS). The current relevant regulation for emission credits relate to the second phase of the EU-wide Emissions Trading Scheme from 2008 to 2012. From 2013, the EU ETS will be modernised so that the EU Member States need not submit national allocation plans anymore. Instead a uniform EU-wide cap/ ceiling for emissions certificates will be in place.

Annual efficiency ratio (net)

It designates the ratio between electricity output of a power plant into the grid together with the fuel consumption in a year required during full operations. Compared to the annual efficiency (gross), the annual efficiency (net) is adjusted to the power consumption of the power plant.

NO

Country code for Norway

SE

Country code for Sweden

Terawatt hours

= 1,000 gigawatt hours (GWh) = 1,000,000 megawatt hours (MWh) = one billion kilowatt hours (kWh): units for electrical work.

Peak load

Peak load refers to the short-term (peak time) high capacity (power) demand in the grid. The peak demands are characterised by a strong increase in electricity demand, to such an extent that the high-speed controllable peak-load power plants need to kick in to cover for the power supply demand. The operating range of the peak-load power plants is between 1 - 2,000 full-load hours per year. They can make high performance capacity available in a very short period of time and become operable in times of absolute peak electricity demand.

Available capacity

It is a theoretical unit/ size applied in models to demonstrate the average available annual capacity of electricity-generating installations. The power available is reflected by the installed capacity of the power plant minus the planned and unplanned downtime. It corresponds to the output of a power plant that can be used continuously and securely for over a year for power generation.

Full-load hours

Describes the ratio, as a theoretical value, of annual electricity or heat generation (GWh) to installed gross capacity (MW) of a capacity generating installation.

Efficiency factor

The efficiency factor generally represents the ratio of emitted capacity to capacity/performance supplied. It is used in power plants to show the efficiency of energy conversion.

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