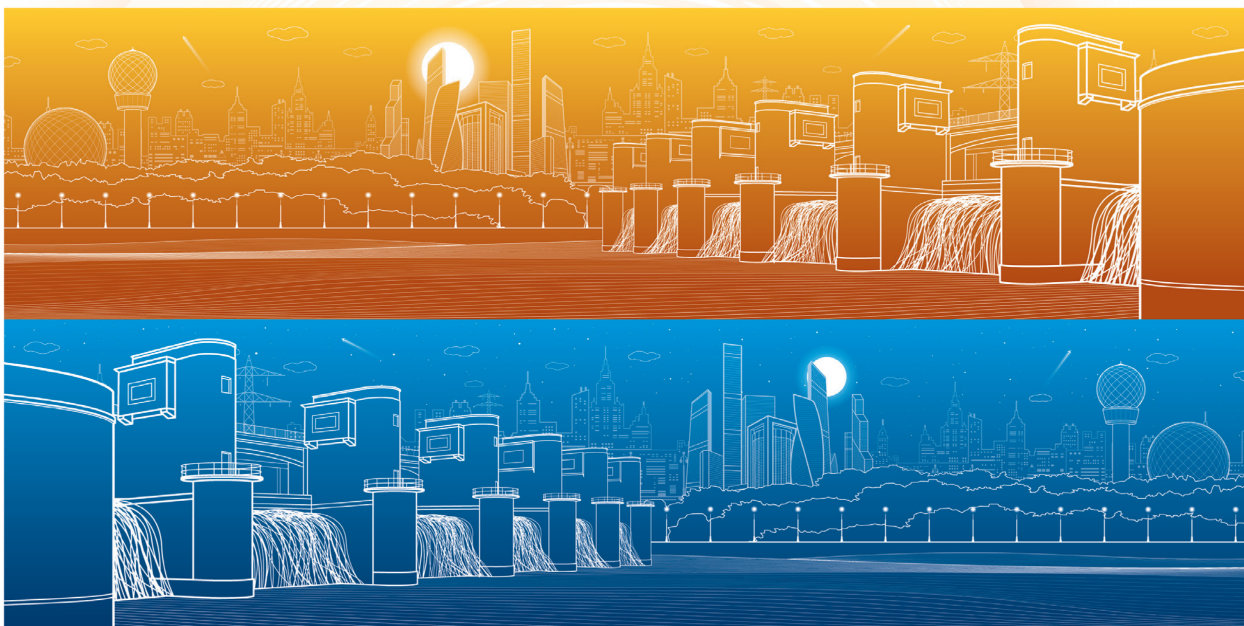
Norwegian Hydropower



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Connecting to Continental Europe

NORWAY IS WELL SUITED FOR HYDROPOWER USE, thanks to its natural geography. This was recognized during the 1800s when Norway started building dams to create reservoirs for storing water for use in hydropower stations. Beginning in the 1950s, the country carried out large-scale hydropower development that lasted for more than 30 years. Norway currently possesses roughly 50% of Europe's entire hydropower storage capacity, with a total reservoir volume of 86 TWh. Norway's large reservoir capacity enables it to be in a position to provide large-scale, cost-effective, and emission-free indirect storage to balance wind and solar generation in other European countries.

The amount of energy that can be provided from hydropower in the Norwegian system varies depending on the precipitation each year. In high rainfall years, there is excess energy, and in low rainfall years, there is a shortage, with the difference being approximately 60 TWh. Norway has mitigated this variation by creating energy-import capabilities for low rainfall years and exporting excess power during higher rainfall years by building interconnections

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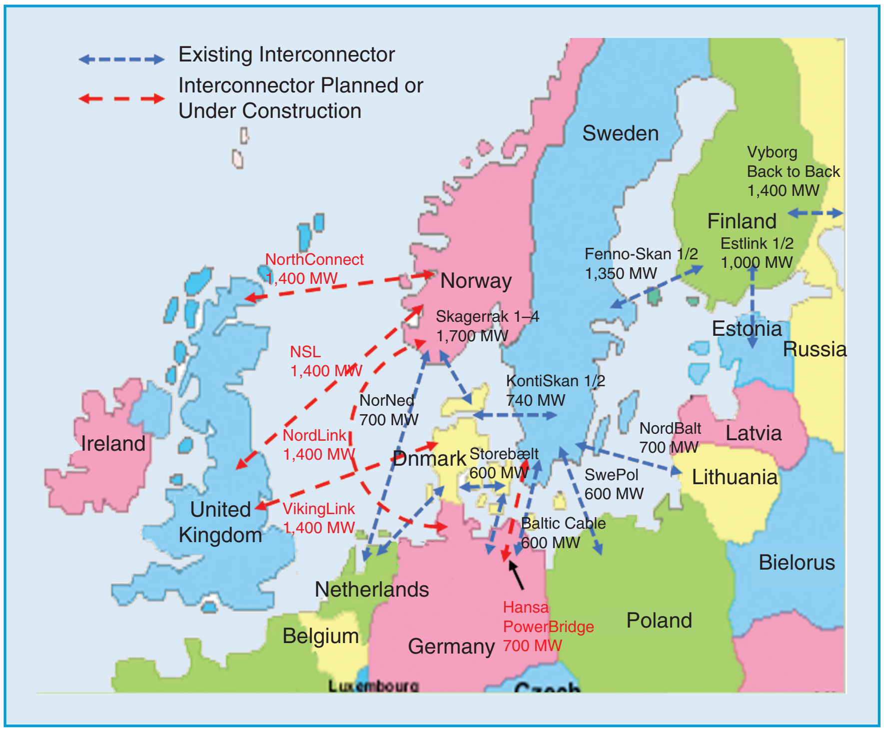

figure 1. The HVdc links connecting the Nordic countries to other areas. NSL: North Sea Link

The Hydropower System in Norway

Hydropower has been important to Norway from its early stages of electrification. Norway's first hydropower station, built by the company Laugstol Brug near the small town of Skien, began operations in 1885 with dc generation equipment supplied by Heyerdahl & Company. In 1890, an early electric streetlight system was supplied from a local hydropower station in one of the world's northernmost towns, Hammerfest. In 1891, a local hydropower station gave the capital, Kristiania (now Oslo), electric streetlights as well. Other early installations included the 1899 Hammeren power station in Maridalen, a two-phase, 5,000-V ac facility; another near Kykkelsrud, a three-phase, 5,000-V ac facility opened in 1904; and the Norsk Hydro power station of 1911 in Rjukan, a three-phase 11,000-V ac facility. These hydro systems used the country's natural resources; therefore, early in their development, concession laws that regulated their utilization were established. These laws have been important for the structured development of the power industry in Norway.

It was important to develop hydropower potential to enable the industrialization of Norway after the Second World War. The majority of the largest power stations in Norway were constructed from the beginning of the 1950s until the end of 1980s. Several of these hydropower schemes were built to supply smelting industries that were being developed near the power stations. After this period, for more than a decade, there was very little new generating capacity. Moving into the 2000s, however, new renewable energy generation solutions came into the market, including small-scale hydro and wind, most without reservoirs.

The installed generation capacity in the Norwegian power system at the beginning of 2019 is provided in Table 1. The peak load in the Norwegian power system is 24,485 MW. The energy balance for the country for the years 2017–2019 is shown in Table 2. The variation in hydropower production,

table 1. The Norwegian power generation capacity, according to Statistics Norway.

Total capacity (MW)	35,348
Hydropower	32,530
Wind power	1,710
Thermal power	1,108

to neighboring countries and submarine high-voltage dc (HVdc) links to continental Europe (Figure 1).

Norway's hydropower resources operate in synergy with wind and solar assets in continental Europe. During times of high wind and solar production, Norway can import inexpensive renewable electricity from abroad, thereby saving water in its reservoirs. During times of low wind and solar production, Norway can use the stored water to export power at higher prices. In this way, excess wind and solar production can be stored and used later.

table 2. The Norwegian energy balance (GWh), according to Statistics Norway.

Year	Total Production	Hydropower Production	Wind Power Production	Thermal Power Production	Import	Export	Gross Consumption
2017	149,402	143,112	2,854	3,436	6,112	21,276	134,238
2018	147,057	139,704	3,877	3,476	8,340	18,489	136,908
2019	134,635	125,796	5,536	3,302	12,353	12,309	134,679

imports, and exports from year to year can clearly be seen. The pump storage consumption in the country was 1,650, 1,031, and 1,262 GWh, respectively, in 2017, 2018, and 2019.

The majority of the Norwegian hydropower stations is a reservoir type, with some run-of-river facilities. There are multiyear reservoirs that can store the normal inflow for more than one year. The largest reservoir is Lake Blåsjø, which has a capacity of 7,800 GWh. There is a limited number of pumped-storage power stations in Norway. The pumping capacity is roughly 1.5 GW. The existing pumping stations were built for seasonal operation (i.e., storage when the snow is melting as well as during spring floods and heavy raining periods, with production during peak load situations and the winter). It became clear that it would be beneficial to connect the Norwegian hydropower system to neighboring networks to compensate for the large variation in the inflow to the reservoirs between wet and dry years (60,000 GWh).

Electricity supply cooperation between the Nordic countries of Denmark, Finland, Norway, and Sweden has long been a tradition. Cooperation sped up after the installation of new interconnections during the early 1960s. In this way, all four countries were joined to a common synchronous area. Western Denmark was the only region synchronously interconnected to the continental European system. The Nordic synchronous area typically had hydropower in Norway, northern Sweden, and northern Finland and thermal power in the south of Finland, Sweden, and eastern Denmark. Transmission systems were developed within the countries at the same time as the construction of new interconnectors to utilize the flexibility of the hydropower system.

In 1976 and 1977, Norway and western Denmark (Jutland) were interconnected with two HVdc submarine cables called the Skagerrak Interconnector. The total capacity was 500 MW. Since Jutland was synchronous with the continental European system, Norway now had a link to central western Europe for the first time. Later, in 1993, Skagerrak 3 was added, with an additional capacity of 500 MW. In 2014, Skagerrak 4 was commissioned, with a capacity of 700 MW, making up a total interconnector capacity of 1,700 MW. In all four countries, the electricity sector used to be dominated by one or a few integrated utilities whose responsibilities were production, transmission, holding a monopoly on exports/imports, and, to different degrees, distribution and wholesale operations. With liberalization during the 1990s, these dominant utilities were unbundled, and the transmission and production parts were organized in separate companies.

In all Nordic countries, the transmission system operator (TSO) model, where the system operator is also the owner of the transmission assets, was chosen. This contrasted with the independent system operator model commonly used in North America. There, the transmission assets are held by separate transmission owners. An important part of the development of the common Nordic electricity market is the power exchange, Nord Pool. The basis of Nord Pool was arranged at the end of 1992 when the Norwegian power exchange, Statnett Marked, was created. When Sweden opened its electricity market in 1996, Statnett Marked was changed to Nord Pool and established as the first international power exchange in the world. Finland joined Nord Pool and the common Nordic electricity market in 1998. The western area of Denmark was included in 1999, and the eastern area of that country was added in 2000.

In a system with approximately 50% hydro, the energy production capability is as important as the capacity margin. Even if there is sufficient capacity to cover peak load periods, an energy deficit may occur during dry years. During normal years, the thermal generation capacity in Denmark, Finland, and Sweden can cover the variations in energy production in Sweden and Norway. During dry years, however, the need to import power may be so large that this capacity will not be sufficient. Plans for the construction of new HVdc interconnections to Germany, The Netherlands, and Great Britain started in Norway during the 1990s to mitigate the supply impact. This has resulted in one new interconnector, NorNed, from Norway to The Netherlands, which was commissioned in 2008. Furthermore, two other interconnectors from Norway are under construction, one to Germany and the other to England.

Connection of Hydropower to Continental Europe

The Nordic power system connects to the continental European power system for the benefit of both networks, as their basic characteristics complement each other. Connecting the systems strengthens the supply security on both sides and is socioeconomically beneficial for the interconnected countries. Figure 1 shows the HVdc links connecting the Nordic countries to other areas. The first interconnector linking the Nordic and central western European synchronous areas was Kontiskan 1, joining Sweden and western Denmark in 1965 with a capacity of 250 MW. This capacity was increased in 1988 with Kontiskan 2, at 300 MW. In 2006, Kontiskan 1 was replaced by a new interconnector of 350 MW. In 1994, the Baltic cable running beneath the Baltic Sea interconnected the Swedish and German power systems. The capacity of the Baltic cable is 600 MW. In 1995, the Kontek interconnector was commissioned, linking the eastern Danish and German power systems. The capacity of Kontek interconnector is 600 MW. The SwePol link between Sweden and Poland was inaugurated in 2000 and has a capacity of 600 MW.

Skagerrak 1 and 2 linked Norway to western Denmark in 1976 and 1977, as mentioned previously. The positive experience and the economic results of the utilization of Skagerrak 1 and 2 triggered the decision to build Skagerrak 3, commissioned in 1993. This fact, together with the liberalization of the electricity supply industry in Norway during the early 1990s, led to the start of several new interconnector projects to link Germany and The Netherlands. The main partners in these projects were large electricity production companies on both sides of the interconnector. As Europe's electricity supply industry liberalized during the 1990s, the large producers, which were mostly vertically integrated companies, were unbundled. These changes in the framework conditions led to a different focus for the production companies. The result was that that none of the planned interconnector projects was realized as planned.

At the beginning of the 2000s, the framework for the industry began to adapt to the new liberalized environment, and there was renewed interest in interconnector projects in Norway and neighboring European countries. This interest led to a restart of the NorNed project, with only the Dutch and Norwegian TSOs as project partners. NorNed will be used as an example and described in further detail later in this article.

Building interconnectors from Norway to continental Europe is not seamless, and a number of challenges had to be solved. The shortest distance between the connecting countries is normally preferred to minimize construction costs. However, electricity systems are typically built to supply power from generation sites to consumption areas. This normally would not fit with a large amount of power importing and exporting in the area closest to a neighboring country. In Norway, the shortest distance to both The Netherlands and Germany is from the southwest area of the country, where the Skagerrak converter stations are already located. Reinforcement of the existing grid was needed to facilitate new interconnector capacity into the transmission system. Therefore, a large transmission system improvement project was begun. This meant both upgrading the main grid from 300 to 420 kV and building a number of new 420-kV lines to the main production areas. A major renovation of the German grid that facilitates north–south transportation is ongoing through the so-called SüdLink project from Wilster to Bavaria.

Changing the energy flow direction on an interconnector has an impact on the control of the interconnected systems. The frequency quality in the systems is affected by the rate of the flow changes. This effect is proportionally larger on a small synchronous system, such as the Nordic one, compared to the larger synchronous continental European system. In addition, experience from the early interconnectors shows that, most often, the Nordic side is challenged when the change in the flow of the cables coincides with the consumption increase in the morning and the consumption decrease in the evening. This causes larger changes in production and transportation as well. In continental Europe, this effect is the opposite. The situation is caused by higher prices during the day and lower ones at night, compared to the Nordic market.

Ramping restrictions have been imposed on the interconnectors to mitigate this issue. To illustrate this situation, Norway can be used as an example. The peak load is 24,485 MW, but the maximum load varies through a large part of the year, between 15,000 and 20,000 MW. When NordLink and the North Sea Link (NSL) are in operation, the total HVdc interconnector capacity in the country will be 5,200 MW. If the change of flow on all the interconnectors takes place at the same hour, it means a change of 10,400 MW. A typical situation is that continental Europe has a higher price than Norway during the daytime and a lower price through the nighttime. According to the market results, the flow on the interconnectors will then go from north to south during the day and south to north at night. As a consequence, when the consumption in Norway starts to increase in the morning, it is necessary to manage the change on the interconnectors from import to export. That means the generators have to pick up both the increase in consumption and, in the extreme case, the 10,400-MW change on the interconnectors. In continental Europe, this will be the opposite: going from export to import will reduce the need for increasing the generator output during the morning pickup. In the evening, this will also be more challenging in Norway since the decrease in consumption goes together with the change from export to import, and again, the downregulation of the generation has to manage both. In continental Europe, this is also the opposite.

As mentioned previously, a common Nordic electricity market was developed during the 1990s. In continental Europe, there were also market developments. The Nordic electricity market covering the Nordic synchronous area and the markets in the synchronous continental Europe area were, from the beginning, not harmonized. There were, among others, different gate-closing times, bid structures, and time resolutions. This created challenges for coupling the markets via interconnectors. A significant effort has been put into the development of harmonized electricity markets in Europe during the past 20 years to mitigate the market harmonization concerns. This market harmonization is still ongoing. The situation has resulted in economic results that are less than optimal compared to the outcomes that could have been achieved with harmonized markets for several of the interconnector projects.

NorNed Use Case

The NorNed initiative started during the mid-1990s as a project between generation companies. Due to the changing environment because of the liberalization in the electricity supply industry, the business case for the program changed, and construction never began. In 2004, the TSOs in Norway and The Netherlands took over the project and the previously negotiated contracts with suppliers of cables and converters. Construction of the interconnector commenced in 2005. The NorNed cable came into operation in 2008, and it continues to function.

Why a NorNed Cable?

There were several positive reasons for constructing an interconnector between Norway and The Netherlands when the investment decision was made in 2004. Generally, an interconnector would strengthen the supply security in both countries. The interconnector would contribute to better resource utilization in both countries' power systems and provide a socioeconomic benefit. In addition, it would have a positive climate footprint by replacing thermal power with hydropower. The following should be noted:

- ✔ Norway and The Netherlands complement each other in energy production and consumption.
- ✔ Consumption peaks during the day in The Netherlands. Norway has a relatively high nighttime energy consumption during the winter, but The Netherlands does not because of gas heating.
- ✔ Production using fast, inexpensive hydropower in Norway complements slow thermal power in The Netherlands (when NorNed was built, there was no wind and solar in The Netherlands).

Figures 2 and 3 illustrate the situation at the time of NorNed's construction in 2005. The project originated as a pure two-countries initiative with an interconnector planned to link Norway and The Netherlands (Figure 1). However, due to the integration of the power systems and the development of regional markets in parallel with the construction, NorNed ended up linking the Nordic market with the central western European market (Figure 3).

NorNed Facts

NorNed consists of a 580-km cable connecting the converter station Feda, Norway, with the converter station Eemshaven, The Netherlands. The submarine cable was, and still is, the longest in the world. It is an HVdc interconnector. The capacity is 700 MW, with an annual capacity for energy transportation of up to 6 TWh. This is enough to supply power to half of Oslo or Amsterdam for one year. The construction cost of NorNed was close to €600 million. Statnett (the TSO in Norway) and TenneT (the TSO in The Netherlands) each own 50% of the interconnector. The planning of the interconnector took 10 years, and the construction consumed three years. The commissioning was in 2008, with the first trading day on 5 May and the first energy delivery on 6 May. Figure 4 shows the converter stations in the flat countryside in Eemshaven and the rocky area of Feda. It also shows the laying of the NorNed cable.

NorNed Results

The remainder of this article will compare the expectations from the project with the actual experiences through the first 10 years of operations of the NorNed HVdc link. In the NorNed project, the plan was to couple the Dutch and Norwegian markets through an implicit auction where energy and transmission capacity were traded at the same time. During the project implementation, it became clear that there would be challenges in the market coupling. There was a parallel development of electricity markets. A common Nordic day-ahead market among Denmark, Finland, Norway, and Sweden was put in place in 2000. In 2006, the so-called trilateral market coupling (TLC) was established by joining the day-ahead markets in The Netherlands, Belgium, and France.

The Nordic and TLC markets were not harmonized, and it was not possible to directly couple them, which had different gate-closure times and bid structures. Attempts were made to find possible market-coupling solutions, but at the time of NorNed's commissioning, an explicit auction solution had to be used. The explicit auction resulted in a two-step process.

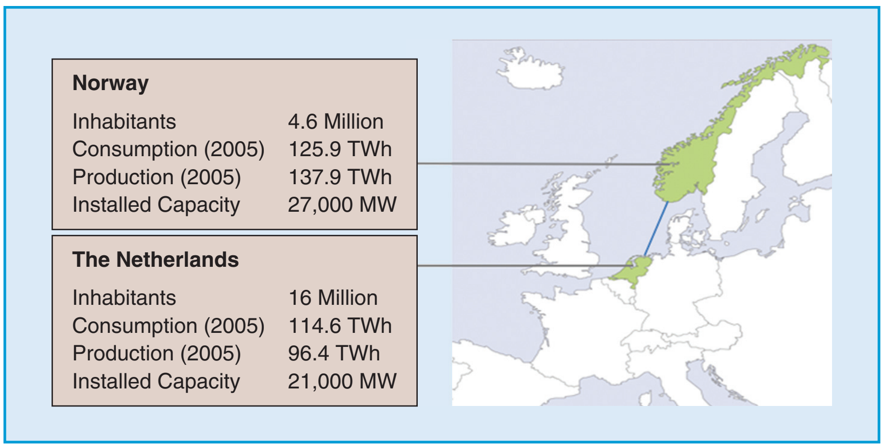

figure 2. The initial arrangement coupling Norway to The Netherlands.

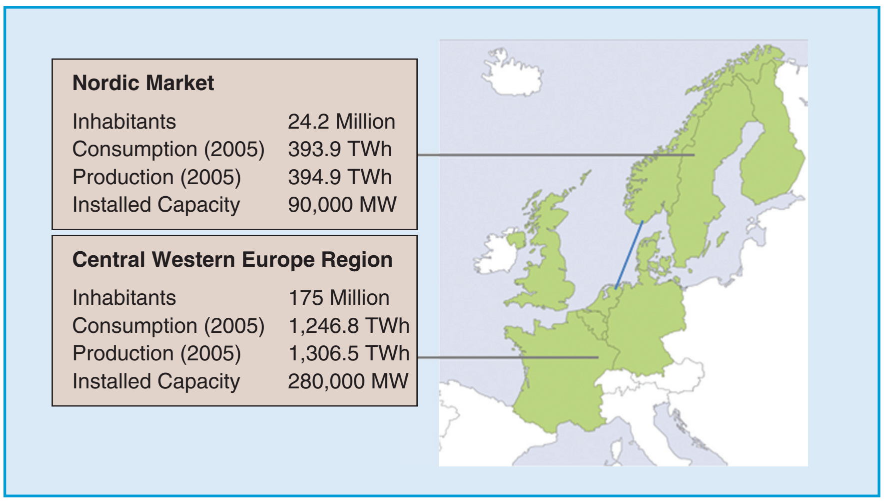

figure 3. The final arrangement coupling the Nordic market to the central western European market.

First, NorNed capacity was auctioned, and thereafter energy trades had to take place in the market on both sides of the interconnector. This two-step execution was not optimal, and in several cases, it led to power flowing in the wrong direction, from a high-price area to a low-price one.

During the first years of NorNed operation, work continued to establish an implicit auction for the trade through the cable. In January 2011, a successful implicit auction for NorNed was held via the European Market Coupling Company, Hamburg, Germany. This was a so-called tight volume coupling, which meant that the volume flowing across NorNed was decided based on all the information from the markets on both sides. Thereafter, the power exchanges on both sides would recalculate their prices in their own region, with the NorNed volume being fixed.

The transaction possibilities across NorNed were expanded when intraday trading was introduced in March 2012. In February 2014, the day-ahead markets in northwestern Europe were successfully coupled, enabling electricity to be traded from France to Finland according to a common day-ahead electricity price calculation based on an implicit auction. Since then, the green areas in Figures 2 and 3 have been one common market. This laid the foundation for multiregional coupling, and in 2014 May, the northwestern Europe region was coupled with southwestern Europe, linking markets and TSOs all the way to Portugal.

Since November 2015, the day-ahead market clearing has been handling implicit losses, increasing the capacity given to the market. Physical losses caused by the power transmission through the cable are included while determining the power flow, avoiding certain hours where the losses exceed the value created by trades. In June 2018, the Europe-wide cross-border intraday (XBID) solution was launched. NorNed was included, and the previous intraday solution was exchanged by XBID.

The availability of the NorNed cable from its commissioning until the end of 2015 was 89%, and the result can be seen in Figure 5. The time to recover the NorNed investment cost of roughly €600 million was slightly fewer than eight years. It can be seen from the availability curve that there has been a number of longer outages on NorNed. This relates to a limited number of large disturbances. In 2009, there were two disruptions: a fault on the land cable in Eemshaven in February and a fire in the ac switchyard in Eemshaven in April. The longest outage was caused by a cable fault during the winter of 2010. Another cable fault occurred during the spring of 2011. In October 2013, a storm damaged the roof of the converter building in Eemshaven and caused water damage.

Figure 6 shows the average amount of energy (gigawatt hour) flowing across NorNed (orange curve) and the average price difference between the day-ahead market price in Feda minus the average day-ahead market price in Eemshaven

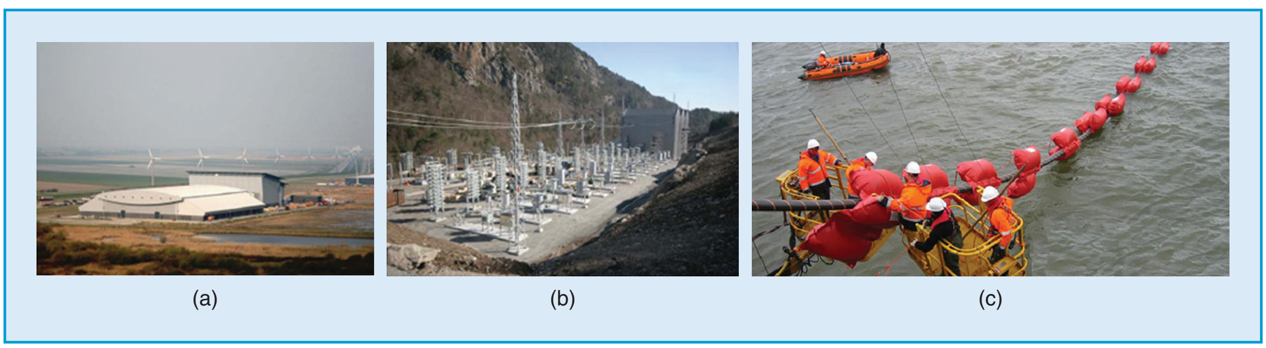

figure 4. The NorNed converter stations and cable installation. (a) Eemshaven, (b) Feda, and (c) laying the NorNed cable.

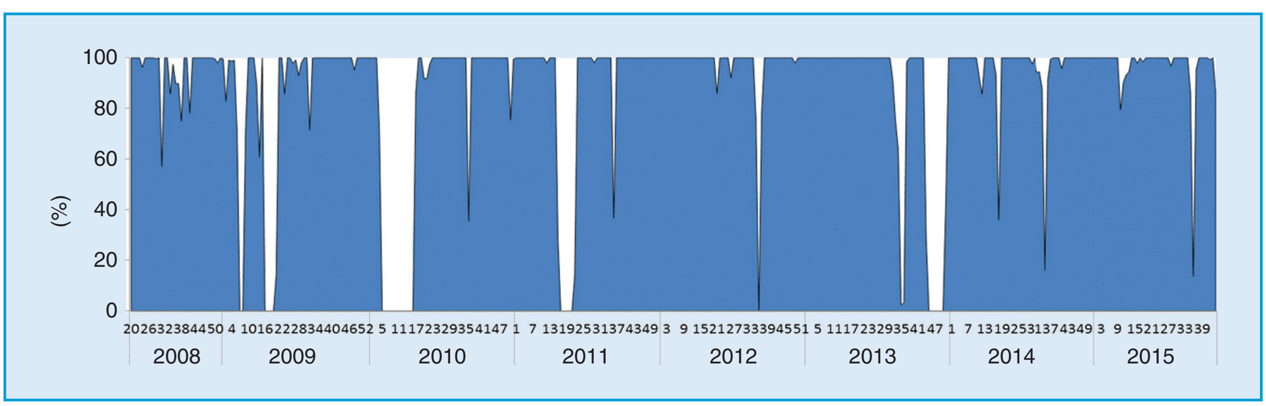

figure 5. The availability of NorNed per week (May 2008–December 2015).

(blue curve). The positive energy values in the figure indicate the flow from The Netherlands to Norway, and the negative values represent the flow from Norway to The Netherlands. With positive price differences, the price in Norway (Feda) is higher than the one in The Netherlands (Eemshaven). Negative prices indicate a higher price in The Netherlands than in Norway. It can be seen from the figure that, more than 80% of the time, the flow has been southward from Norway to The Netherlands. But it can also be seen that in 2010–2011, when there was a dry year in Norway, the average flow was from The Netherlands to Norway. This clearly demonstrates how the interconnector strengthened the security of supply in Norway during this period.

Looking at the past five years, much more variation can be seen in the flow. This comes as more volatile wind and solar capacity entered the Dutch and continental European systems. The figures show average values; if we look at hourly values, changes in the flow direction can be observed. The income to the owners of the interconnector comes from the congestion rent, which is equal to the price difference between the market areas multiplied by the transmitted volume of energy. The overall socioeconomic benefit from the interconnector has provided producer and consumer surpluses, in addition to the congestion rent for the owners.

The effect of NorNed on the market can be seen as a reduction in price spikes, both high and low. In a wet-year surplus in Norway, energy can be exported, and the prices will stay higher, giving a producer surplus. In addition, there will be less water spilled from filled reservoirs. In The Netherlands, this situation will result in the import of lower-priced electricity and lead to a consumer surplus. In a dry year, the flow will go from The Netherlands to Norway and result a lower price in Norway and, by that, a consumer surplus. In The Netherlands, a dry year will lead to a producer surplus.

Figure 7 shows the hydrological balance in the Norwegian hydropower system, in gigawatt-hours, referred to the normal value together with the day-ahead market price. The hydrological balance is the sum of the content in the reservoirs, snowpack, and ground water. The figure shows that during the winter of 2010–2011, there was a very low hydro balance in the system and that, at the same time, the day-ahead price was high. For the years 2014–2017, the hydrological balance was good, and the day-ahead prices were low.

Environmental Impact

For almost all Norwegian hydropower stations of the reservoir type and above a certain size, the station hall is located within a mountain. This means that the effect on the environment outside these power station installations is limited. On the other hand, the construction of reservoirs for hydropower stations implies the building of dams, which will have consequences for the wildlife and the environment in the area where they are built, during both construction and operation.

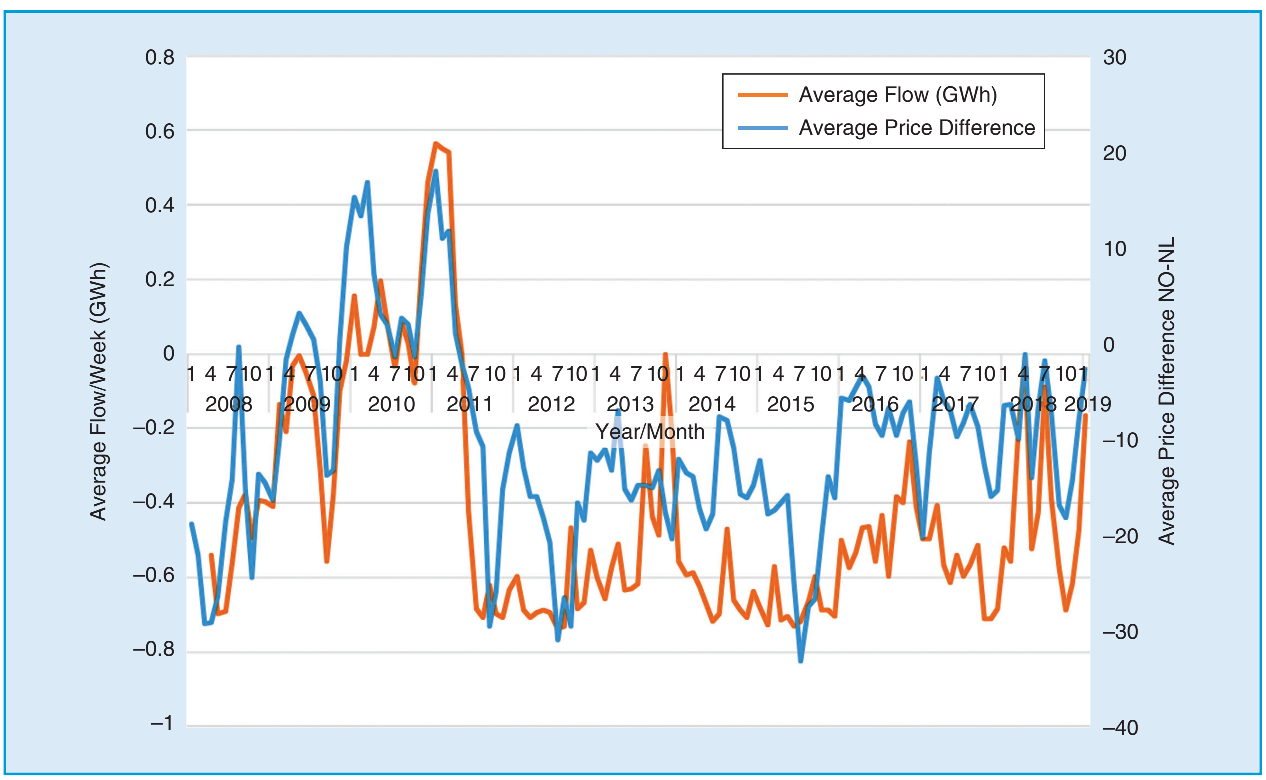

figure 6. The average flow per week (gigawatt hour) on NorNed and the average price difference between Norway and The Netherlands (in euros). Negative values indicate a higher price in The Netherlands than in Norway.

When the reservoir is full, it can look like any lake, but when the water level is low, the shores appear like a deserted area.

When the majority of Norway's hydropower stations were erected (from the 1960s to the 1980s), it was more imperative to build the country's infrastructure and provide electricity than it was to preserve nature. More recently, there has been significant opposition to the planning and construction of new hydropower plants. The same goes for large wind parks, which are now being built. However, most of the construction takes place in remote areas, meaning that there is a limited number of people being directly impacted.

The downstream flow of water will be affected by the production of the power station for run-of-river power plants. This is based on the electricity markets. There are, however, conditions given in the concession for building a power plant that govern how to operate and secure a minimum flow of water in a river. Similarly, there may be rules for the maximum flow in a river. In this way, a power plant helps to control the flow of water in a river during flood situations.

Social Impact

Creating hydropower reservoirs through the construction of dams can potentially cause a social impact in addition to the more evident influence on the environment. If the possible social impact of creating hydropower reservoirs is not observed and dealt with in time, great opposition can result. The social impact can be presented in several ways, the most severe being the displacement of residents whose homes would be flooded by a reservoir. Residents often protest against the projects and try in every possible way to prevent construction. Even if communities are resettled and there are no negative financial consequences (the company or authority demanding the resettlement provides a fair financial compensation), residents are still taken from their homes and need time to relocate. For some, this could result in life-long difficulties and a lower quality of life.

A further social impact is experienced downstream of a dam. Since the availability of water in a river is no longer natural, it is heavily influenced by the amount let through the dam. This is, in fact, ruled by the electricity markets, not by nature and seasonal changes. This can be a problem if the river is also used for irrigation, transportation, and recreation. Often, the residents who are negatively affected by the construction of a hydropower reservoir are not the same people who benefit the most. The residents experience only the downside, while others will profit. Since hydropower plants in Norway are mostly located in remote areas, the impact is often felt by a small number of people and local communities. It should be noted that the municipalities with larger hydropower stations are among the wealthiest in the country, and they can often offer better services to their residents than what is common elsewhere.

What Are the Current Developments?

The current developments are dominated by the deployment of new renewable resources: wind and solar in continental Europe and small-scale hydro and wind in Norway. Most of these mean noncontrollable capacities. As a consequence, flexibility in other resources in the production systems is becoming more important and will be more valuable. Since 2003, there has been a common balancing market for the exchange of reserves in the Nordic countries. In continental Europe, there has been cooperation in the development of an integrated balancing mechanism. The cost of keeping reserves in the power systems has been reduced by this type of cooperation.

Even though there is cooperation at a regional level to optimize the balancing of the power systems, there is still considerable

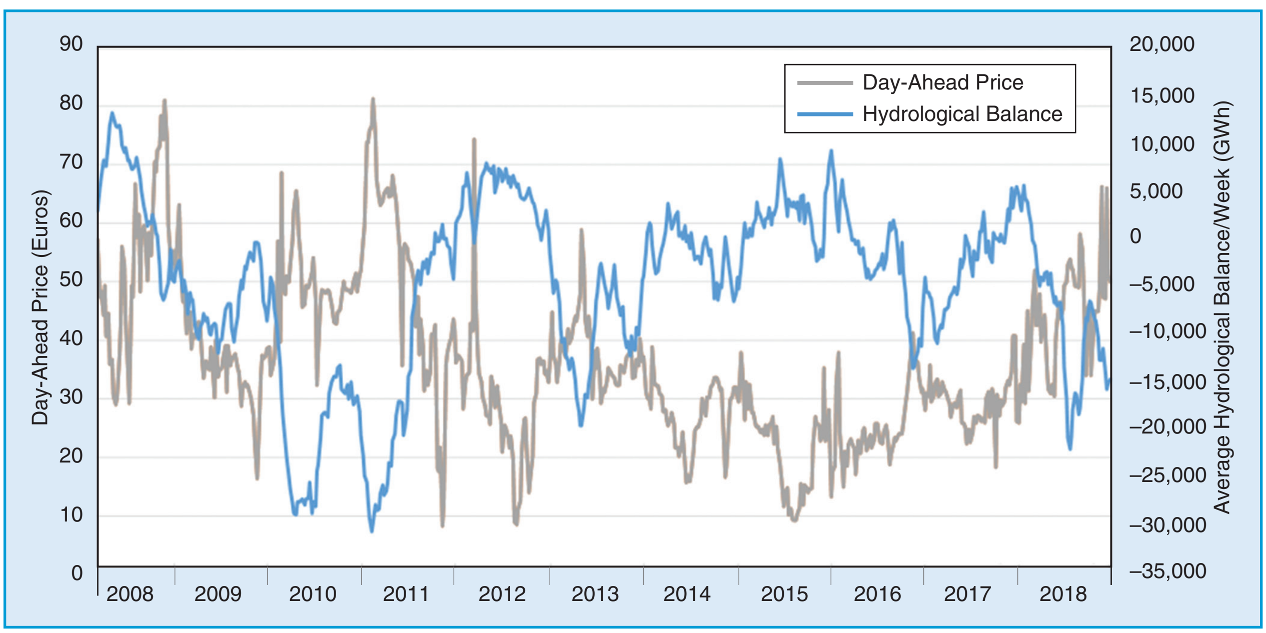

figure 7. The average hydrological balance per week and the day-ahead prices.

of development needed to produce a harmonized common balancing market in Europe. There are several ongoing projects to develop and implement markets for the different balancing products that are used. These solutions will be based on a number of platforms for the exchange of reserves with different time responses. For NorNed, there have not been exchanges of reserves; however, when the new platforms are in place, reserve exchanges are expected to be available on this interconnector. This can add more to the benefits of the link.

The Role of Norwegian Hydro in Meeting European Climate Goals

In high rainfall years, there will be excess energy in the Norwegian reservoirs, meaning there is more water running into the reservoirs than needed for meeting the country's electricity demands. At some point, this influx could result in the reservoirs being fully stocked. To avoid wasting this energy and letting it out via a bypass, it is better to produce electricity and transport it to other countries in Europe. Therefore, Norwegian hydropower directly contributes to the climate goals of Europe since, as a result, high-emitting thermal power plants can run down or even stop their production.

Another way to help reach European climate goals is to balance the production of renewable sources, such as wind and solar. The ever-increasing penetration of wind and solar power throughout Europe presents society with challenges related to the volatile nature of those resources. This can result in production that exceeds demand on a sunny and, at the same time, windy day, perhaps during the summer holidays, when demand is low. It would be unfortunate to regulate down the renewable sources and waste their energy, and it would be better to sell this excess energy for a lower price to Norway. In that country, this will result in reducing the generation from the hydropower plants, thus keeping the water in the reservoirs. In this manner, the renewable energy coming from wind and solar is stored (indirectly) in the Norwegian reservoirs. If, in the future, there is little wind and solar energy being produced, the hydropower plants can speed up, and the originally stored energy can be released and sold for better prices back to continental Europe. Therefore, there are financial benefits in both systems, and the available wind and solar power is better utilized to help reach European climate goals.

There are, of course, limits to the possibilities of both the connections between Norway and the surrounding systems, such as continental Europe and the capacities of the reservoirs. This means there are limits to the amount of energy that can be transported to and from Norway and that the storage capacity of the reservoirs is limited. Remember that the natural inflow coming from rain and melting snow and ice need to be taken into account.

Outlook for the (Near) Future

If the exchange of energy between Norway and the neighboring countries in continental Europe and the United Kingdom is to be increased, new interconnector capacity and flexible production facilities in Norway are needed. Regarding interconnector capacities, there are already two projects in the construction phase. The NordLink project between Norway and Germany, with a capacity of 1,400 MW, is scheduled to be commissioned in 2020. The new interconnector will be owned by Statnett and TenneT Germany. There is also a project linking Norway and Great Britain, the NSL. This interconnector will also have a capacity of 1,400 MW. Owned by Statnett and National Grid, it has a planned commissioning at the end of 2021. Furthermore, the NorthConnect project, linking western Norway to Scotland, is currently in the licensing process. This cable is also planned with a capacity of 1,400 MW.

There is an expected need for more flexibility to control the increasing amount of volatile wind and solar production. This flexibility is also assumed to become more valuable. In Norway, it can be found either by utilizing the existing system more effectively or building new capacity. In the latter case, new pump storage plants can be interesting. The existing Norwegian pump storage plants were built for seasonal operation. There have been research projects and plans looking into new pump storage installations. The most interesting concept has been to look for an existing power station with reasonably large reservoirs both upstream and downstream. There are several possible locations for such a project. It has, however, been found that it is not economical to start developing a project further. Studies have shown that the Norwegian and Nordic systems can manage a considerable increase in noncontrollable generation. Because of this, it is hard to find economy in new pump storage plants in Norway in the short term.

The expectations from project developments 20–30 years ago have been fulfilled. The development of large amounts of uncontrollable wind and solar resources has increased the value of the interconnectors, both economically and environmentally.

For Further Reading

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