ELECTRICITY SECTOR INTERACTIONS BETWEEN NORWAY AND EUROPEAN CONTINENTAL COUNTRIES

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ABSTRACT
This paper explores how Norway's electricity sector may interact with continental European ones, notably Germany, in respect of mitigating the need to manage the variability of renewable electricity generation on the continent. Norway's system has capabilities for providing flexibility for responding to variations in wind and solar generation and consumption. The variability of residual load in Germany over a recent multi-year period is analysed in terms of instant shortfalls and cumulative shortfalls of electricity supply that would arise if Germany's renewable generation increases to match its consumption in recent years on average. It is found that interactions with Norway's system cannot remove any large part of Germany's need for flexible generation capacity to cover instant shortfalls, but can significantly reduce the cumulative amount of electricity over time that needs to be supplied from such flexible capacities. The capabilities and constraints in Norway's system for providing such flexibility are analyzed, as are economic implications for Norway.
Keywords: energy transition, flexible power, German electricity, hydropower reservoirs, Norway electricity, renewable generation, residual load, shortfall, variable power.

1 INTRODUCTION

The uncontrolled variability of wind and solar power generation is recognized as a major challenge for countries moving towards carbon neutral electricity systems. Germany and several other countries in continental Europe face costly measures for acquiring the flexibility needed for securing continuous power supply when phasing out fossil generation. Norway's electricity system has resources that potentially offer such flexibility, notably its large water reservoirs for hydropower generation.

This paper explores the relevance and viability of Norway's electricity system as a source of flexibility for other countries. The analysis focuses on Germany as the country with which Norway would mainly interact, partly because of Germany's large size and partly because Germany has strong ambitions for replacing fossil with renewable power generation. Germany's renewable power generation and residual load variability are analysed in terms that are relevant for its interaction with Norway's system. Norway's electricity system is reviewed to identify capabilities and constraints for its interactions with continental systems. Implications for Norwegian electricity sector economics and other priorities are identified.

Several authors and research institutions have modelled scenarios for Germany's future electricity system with a high or complete share of renewables in the generation mix. The need for energy storage, mainly in the forms of hydrogen by electrolysis, batteries and pumped hydro are central output parameters and drivers of system costs in such scenarios. Schill modelled German residual load durations, requirements for energy storage and system costs under several future scenarios, including a scenario for 2050 with 20% of German power consumption still supplied by fossil fuels [1]. He assumed no cross-border electricity trade. He found surplus generation requiring storage (or production curtailment) ranging from 18 TWh to 195 TWh as mean simulation values depending on whether the remaining 20% fossil generation and the biomass based generation could be run flexibly or not. Schill and Zerrahn took this work further to develop a generalised model for power storage requirements with high shares of renewables [2]. The Fraunhofer Research Institute in 2021

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modelled the future German electricity system and need for flexible system components as a basis for proposing market design [3]. The Agora Energiewende Institute modelled a scenario in which German electricity generation would nearly double from recent levels to 2035, with nearly no remaining fossil generation [4]. This scenario would require 76 GW of flexible generation, predominantly from hydrogen and/or derived gases, in addition to large capacities for battery and other short-term storage. The research institutions Fraunhofer IEE (Germany) and SINTEF (Norway) are currently engaged in a joint research undertaking, named HydroConnect, studying how Norwegian hydropower can contribute to the energy transition in Europe [5].

2 METHOD AND DATA

2.1 Approach

The paper draws on analysis of quantitative data, mainly time series, on sources, application and prices of electricity in Europe to inform the research issues raised in the introduction.

Using recent historic data, scenarios are built for how a future German electricity system based fully on renewable generation will be challenged in terms of variabilities of generation and consumption, how interactions with Norway's electricity system may help mitigate those challenges, and implications of this for Norway. The modelling approach applied here is simpler than for the studies referred in the introduction, which were based on comprehensive bottom-up approaches for scenario modelling of all major system components. This study, in contrast, makes direct use of historical time series for generation, load, prices and cross-border transmission.

2.2 Data sources

The European Network of Transmission System Operators for Electricity, ENTSO-E, publishes data on electricity generation by type, load (consumption), export, import, and trade prices of electricity [6]. This is published as time series of one hour, in some cases of 15 minute intervals. These time series are the main data source for the analysis in this paper.

The time series apply to bidding zones as reported by ENTSO-E. A bidding zone generally has sufficient transmission capacity internally to avoid the need for geographic differentiation of trade prices within the bidding zone. Norway has five bidding zones (NO1 to NO5), whereas Germany forms one bidding zone together with Luxembourg (DE-LU). Before 1 October 2018, Austria was part of the joint bidding zone with Germany and Luxembourg, for which reason the main analysis in this paper cover time only after that date.

Supplementary data from other sources are referred in the subsequent text where applied.

2.3 Benefits and limitations of the ENTSO-E data

The ENTSO-E transparency platform time series are generated from data reported by national system operators. ENTSO-E has issued references to guide this reporting, as found on its web site.

Hirth et al. assessed the transparency platform and found significant scope for improvements, including a proposal to notify users about issues with data quality [7]. This proposal does not appear to have been implemented at the time of writing.

The ENTSO-E data have a rich level of detail, notably the granularity of its time series. This allows for analysis of dynamics and interactions of essential parameters of electricity sector operations: power generation from different resources, consumption, flows between bidding zones, and prices.

There are issues with the completeness of the data on the ENTSO-E transparency platform. For the Germany–Luxembourg bidding zone, the time series on generation, load and transmissions cannot be balanced to zero difference. Other German statistics show significantly higher numbers for net electricity generation than those obtained by summation of the ENTSO-E data (for example, statistics provided on https://de.statista.com/).

The focus of this paper is on dynamics of the electricity sector, more than on periodic totals. It aims for a level of numeric precision for which the stated issues with the data are assessed as tolerable.

2.4 Electricity shortfalls: Instant and cumulative energy

Residual load is the part of electricity consumption that is not supplied by renewable energy, notably wind and solar generation. Those forms of renewable generation are highly variable and largely uncontrollable. Consumption is in this context treated as largely uncontrollable, even though it is the aggregate result of many individual decisions.

A derived concept applied here is *electricity shortfalls*. An electricity shortfall arises when a source of electricity supply falls short of its longer-term average rate, or when a residual load is larger than a longer-term average. The opposite of shortfall is referred to as excess. The reason for focusing on electricity shortfalls is that the electricity system must be balanced at all times, for which those uncontrolled variabilities must be offset by controlled variability in other parts of the system. Electricity shortfalls is a concept for quantifying this.

Two expressions of electricity shortfall are applied here. An *instant shortfall*, measured in GW, arises whenever generation falls short of a long term average rate for a 15 minute period. A *cumulative shortfall*, measured in TWh, arises as the aggregate over time of instant shortfalls, net of offsets when there is excess.

Table 1 shows characteristics of different levels of residual load, for the Germany and Luxembourg bidding zone, for the period of 5 years ending 30 September 2023. The shortfalls are computed against the average load and residual loads for that period. Residual loads and shortfalls are shown as negative numbers.

Table 1: Variability of residual loads. Germany and Luxembourg, 1 October 2018–30 September 2023. *(Source: Based on data from ENTSO-E [6].)*

Residual load level	A. Average (GW)	B. Standard deviation (GW)	C. Largest instant shortfall from average (GW)	D. Largest cumulative shortfall from average (TWh)
1. Load (Consumption)	−56.2	9.7	−25.9	−44
2. Residual load with wind and solar	−36.5	12.5	−38.8	−54
3. Residual load with all renewables	−30.4	11.2	−35.6	−50

As shown in Table 1, Germany had an average load of 56.2 GW over the period, Solar and wind supplied an average 19.7 GW, leaving an average residual load of 36.5 GW. The combined variability of wind, solar and consumption caused the residual load to exceed its average by 38.8 GW on a brief occasion (column C), and by 54 TWh as a cumulative energy

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shortfall (column D). The other renewables, notably hydro and biomass, reduced the instant shortfall to 35.6 GW, and the cumulative shortfall to 50 TWh. These reductions of shortfalls are due to the relative stable provision of these power sources and some flexibility to vary them in response to residual load variations.

Fig. 1 shows cumulative deviations from the average load and the average residual load with wind and solar generation. The lines drop in periods of higher than average consumption, with the dotted line representing consumption not covered by wind and solar. The graph covers a period in which electricity consumption was higher early in the period than towards the end, for which reason the entire value set is below the zero line representing average loads. The largest cumulative shortfall of 54 TWh (as in row 2, column D of Table 1) appears in Fig. 1 as the drop of the dotted line to its lowest point in early 2022 from its previous highest point. After that time, the cumulative shortfall was offset by lower consumption (related to the Ukraine crisis) and stronger winds. More comments on the parameters shown in Fig. 1 are provided in Section 4.

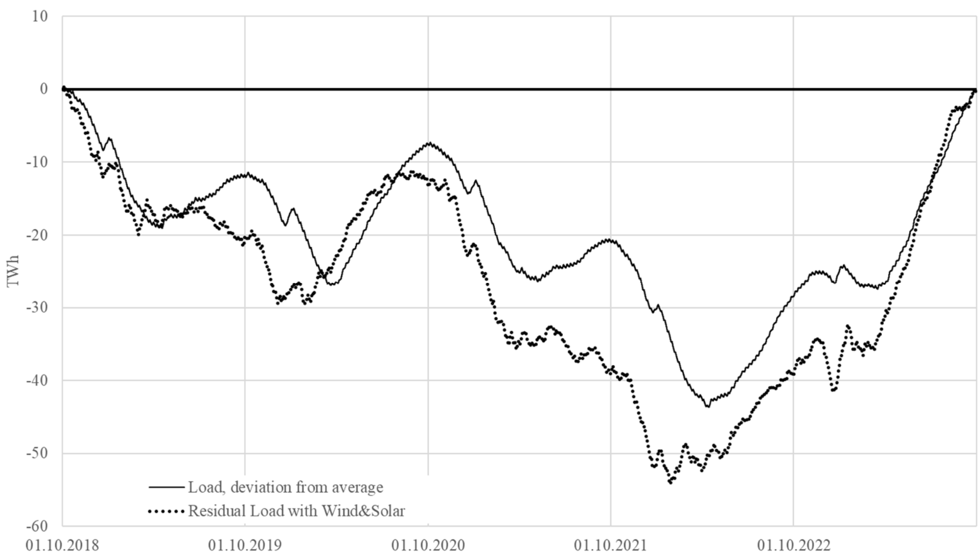

Figure 1: Cumulative deviations from average residual load. Germany and Luxembourg, 1 October 2018–30 September 2023. *(Source: Based on data from ENTSO-E [6].)*

The concept of electricity shortfalls and excess is found useful for quantifying the variabilities of consumption and renewable generation in Germany in a way that can be related to Norway's electricity resources. The concept has certain limitations, notably concerning the determination of the average loads to which the shortfalls are related. As seen in Fig. 1, the cumulative deviations start and end at 0 over the defined reference period. This follows from the definition of the concept. The average, represented by the horizontal 0 line in Fig. 1, is known only in retrospect, and depends on the chosen reference period. To perform a similar analysis for an ongoing period, one would have to base it on forecasted residual loads, which will turn out to be more or less accurate.

3 NORWAY'S ELECTRICITY SYSTEM: SOME CHARACTERISTICS

This section gives an overview of Norway's electricity sector, highlighting differences with systems on the European continent and also highlighting features affecting interactions between Norway's and other electricity sectors. Numbers cited are from Statistics Norway (ssb.no) where no other source is indicated.

Hydropower predominant. Hydropower contributed 88% of generated electricity in 2022; wind, 10% and thermal power, 2%. There are no large thermal power plants.

Large electricity generation relative to Norway's population and economy. Norway generated 146 TWh of electricity in 2022. That was 25% more than the electricity consumption of the Netherlands, a country with a population more than three times that of Norway. Norway's population at the end of 2022 was 5.5 million.

Large consumption of electricity, as a result of policy choices. Consumption in 2022 was 133 TWh, including 8 TWh consumption in production and transmission. The abundant resources for hydropower were developed at times when there were limited possibilities for large power transmission across long distances. This has motivated policy and commercial choices of large-scale uses of electricity not common elsewhere in Europe. Following are four such policy choices, the first two of which date back to the first half of the 20th century.

- **Large power-consuming industries**. Industries categorised as power-intensive consumed 39 TWh of electricity in 2022. This includes a large aluminium industry using electrolysis to extract aluminium from ores, which are all imported.
- **Predominant use of electricity for space heating of buildings**. Households consumed 6,900 kWh of electricity per person in 2022.
- **Electricity from the grid for petroleum installations**. All petroleum production occurs offshore, with some processing plants onshore. The installations have historically generated their own electricity from produced gas. A policy is in place to replace such power generation with electricity from the domestic grid. 9 TWh of electricity were consumed for this in 2022, and the amount is projected to grow.
- **Electric vehicles and short-distance shipping**. More than 80% of passenger cars recently sold in Norway have no combustion engine. Some 2 TWh of electricity is spent annually on electric vehicles and ships.

Large water reservoirs for hydropower. The reservoirs can hold 87 TWh of potential hydropower, which is 65% of recent annual consumption. Large reservoir capacity is essential for Norway's hydropower to provide for consumption in winter, when heating needs are high and precipitation falls as snow on mountains. Reservoir content follows a seasonal pattern: Filled up high before winter in November, and reaching a minimum in April as mountain snow starts melting. In a median year, as defined by the energy directorate, the difference between high and low reservoir content is 45 TWh, but it has been as high as 59 TWh (https://www.nve.no/energi/analyser-og-statistikk/magasinstatistikk/). Some large reservoirs take several years to refill if they have been depleted.

Limited room for more hydropower development. Large hydropower developments were mostly completed by 1990. Since then, the annual growth rate of hydropower generation has been 0.6% per year, as there have been some small-scale development and upgrade of existing facilities. The remaining potential is constrained by natural preservation regulations.

Wind generation has increased in recent years, and is controversial. Wind generation was 15 TWh in 2022 – nearly quadrupled since 2018, but not very impressive next to Germany's 123 TWh. In recent years, opposition to wind farms has become quite vocal, and the planning of further onshore wind farms has largely become stalled.

Large potential for offshore wind, but costly. The Government has set an ambitious target of 30 GW offshore wind by 2040. Norway largely lacks offshore areas suited for wind turbines standing on the seabed, which are common elsewhere. Whether the cost of floating wind can come down to acceptable and competitive levels, remains uncertain.

Little solar generation. ENTSO-E reports no solar power generation in Norway. Construction of some solar power plants is just starting as of 2023. Some homes and other buildings have photovoltaic panels, from which surplus electricity is sold on the grid.

Large distances and transmission bottlenecks. The Norwegian mainland is 1,700 km from the southern to the northern end. The domestic transmission system sometimes lacks the capacity to move desired amounts of electricity, the need for which varies much between years. The country is currently divided into five bidding zones for electricity. In recent years the two northern zones (NO3, NO4) have had much lower electricity prices than the three southern ones. Sweden effectively functions as a transit for moving electricity between Norway's north and south, but Sweden has its own grid limitations. Large investments are planned in upgrading the Norwegian transmission grid, but limitations will likely persist for quite some time [8]. The terminals for Norway's trade in electricity with the European continent are in the south, and effective capacities for trade are affected by transmission limitations within Norway.

Mostly public ownership. Most hydroelectric production and reservoirs are owned by energy firms that are owned by the state and municipalities, with Statkraft (100% owned by the Norwegian state) as the largest player. Some industrial firms in power-intensive industries own long-established power plants. Small hydropower plants tend to be owned by private investors, often with the involvement of local landowners. Onshore wind farms are owned by a mix of public, local and commercial interests, including investment vehicles whose funds originate from foreign pension funds.

4 RENEWABLE ELECTRICITY GENERATION IN GERMANY

Successive German governments have upheld the ambitious goal of ending the use of fossil and nuclear fuels. The goal of ending dependence on fossil fuels achieved a renewed urgency as the Ukraine crisis from 2022 became a reminder of the perils of being dependent on large imports of hydrocarbons.

Timed objectives have proven elusive, but significant achievements have been made: According to one source, Germany's power generation from renewables was 236.5 TWh in 2022, up from 1.8 TWh in 1992 (Statistical Review of World Energy, published in 2023 by the Energy Institute, and in earlier years by the energy company BP [9]). The ENTSO-E hourly data are summarised in Table 2 for renewable and other power generation during a recent 5 year period.

Following are some comments on the variability of energy sources for generation as indicated by the data for minimum, maximum and standard deviation in Table 1.

Wind and solar generation, once operational, are variable due to seasonality and weather, i.e. largely beyond human control. The variability of wind and solar are to some extent offsetting, as there is usually more wind and always less sun in winter than in summer. Especially wind has large day-to-day variations, as shown in Fig. 2.

Fig. 1 shows the cumulative effects of the variations shown in Fig. 2, with the added component of load variations. Taking the average residual load during the 5 years to 30 September 2023 as reference, most winters saw an increase in cumulative shortfall (shown as falling curves in Fig. 1), as stronger winter winds could not make up for higher consumption and lower solar in winter. The cumulative shortfalls were offset in the springs

Table 2: Electricity generation in Germany and Luxembourg, 1 October 2018–30 September 2023. The generation data shown in are for net generated electricity delivered to the grid. The minimum, maximum and standard deviation figures are based on 15 minute intervals throughout the 5 year period [6].

Energy source	Average TWh/year	Minimum power GW	Average power GW	Maximum power GW	Standard deviation GW
Wind, onshore	100	0.1	11.4	45.6	9.1
Wind, offshore	24	0.0	2.8	7.6	1.9
Solar	49	0.0	5.6	41.0	8.7
Biomass	40	3.6	4.6	5.2	0.3
Hydro incl. pumped*	12	−7.4	1.3	10.9	2.6
Other renewable	8	0.1	0.9	0.2	0.0
Sum renewables	233	1.5	26.6	66.5	11.5
Nuclear	51	0.0	5.8	9.5	2.7
Natural gas	54	1.2	6.2	19.8	2.8
Coal	145	3.6	16.5	33.8	6.7
Other non-renewables	6	0.1	0.7	1.5	0.2
Sum non-renewables	256	6.4	29.2	57.8	9.9
Sum generation	489	19.7	55.8	86.8	11.7

*Generation from pumped hydropower is included, and power spent pumping is deducted.

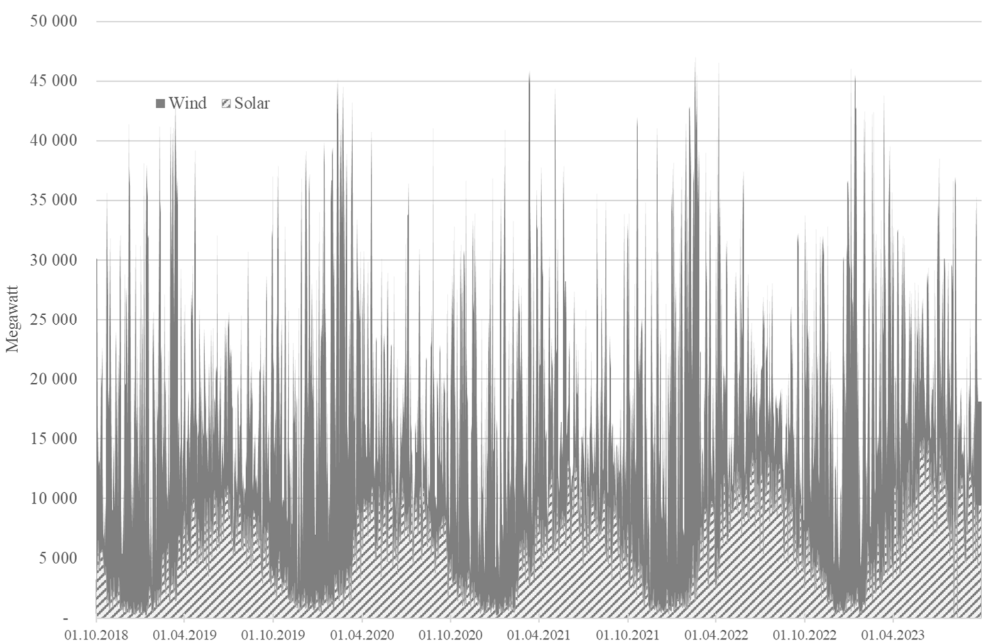

Figure 2: Wind and solar generation, Germany and Luxemburg, daily averages. *(Source: Based on data from ENTSO-E [6].)*

and summers, especially in 2020, 2022 and 2023, which were years of relatively low energy consumption.

The variability shown for nuclear generation is mainly due to nuclear plants having been taken out of service during the period. When operating, nuclear power plants tend to generate at quite stable rates.

The other types of generation are variable largely by human intent, in response to uncontrolled variations in the residual load (consumption not supplied by wind and solar). They differ in their flexibility to provide controlled variations.

Hydropower provided just 2.5% of net generation, net of power spent for pumped hydro. The net generation comes from run-of-river plants, whose variability is largely uncontrolled. Pumped hydro is a negative contributor to net generation, since 29% more energy was spent pumping water into high reservoirs than was obtained when drawing from them. Pumped hydro can respond to uncontrolled variations in the residual load, but the capacity for this in Germany is rather limited: The largest generation from pumped hydro during the 5 years was 8.8 GW. Such a rate would be sustainable for no more than a few hours, as the largest consecutive drawdown was 53 GWh.

Biomass is a significant source of electricity with 8% of net generation, with much less variability than wind and solar. Its biggest component is combustible gases obtained at some 10,000 farms, sewage treatment plants, etc. [10]. Solid biomasses are obtained from agriculture, forestry, and other sources. In principle, biomass fuels can be stored for use when their value is greatest. In practice, this does not happen much in Germany. (A correlation coefficient of 0.42 for biomass generation against electricity price was found. Slope: 0.03% additional electricity from biomass with 1% higher electricity price.) Unprocessed biogases are generally of a composition not compatible with natural gas pipeline requirements. The cost-effective solution is often to generate electricity from it at the production location. Nevertheless, electricity generation from biomass in Denmark shows a significantly larger response to price variations and seasonal needs than in Germany [6].

The flexibility needed to offset uncontrolled variations in the residual load has been provided mainly by fossil-based generation in Germany. A small part of the flexibility needed has come from variations in cross-border trade. Generation from natural gas shows more flexibility than coal in responding to residual load variations. This is indicated in Table 2, as maximum generation and standard deviation are higher, relative to average generation, for natural gas than for coal.

Such flexibility also depends on the generation technology used. There are trade-offs between flexibility and energy efficiency. Open cycle gas turbines is a highly flexible generation technology for responding to surges in power demand, but their thermal efficiency is usually less than 40%. Higher energy efficiency can be obtained from combined cycle gas turbines, and from combined heat and power plants using gas and other fuels. Some 120 TWh electricity per year is generated in Germany in plants that also deliver heat to industrial applications or district heating [11]. Such plants may be constrained in their flexibility for varying electricity generation because of the need to match local heat requirements.

5 SCENARIOS WITH RENEWABLE GENERATION MATCHING CONSUMPTION

Germany's aim of eliminating its dependence on fossil and nuclear fuels requires that renewable generation increases to match consumption, unless it would start to rely on large net imports. The assumption made here is that cross-border trades would be largely balanced as averages over several years, but allowing for shorter-term imbalances. Germany would then turn from net exporter to a balanced trader of electricity.

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Germany's electricity consumption has been on a declining trend since 2007, but this may turn to growth as the country seeks to decarbonize much of its energy use. The following analysis does not incorporate any assumed change in electricity consumption, in terms of total amounts and variability, compared to the 5 year period to 30 September 2023. The German studies cited in Section 1 assumed strong increases in electricity consumption over the next 15–20 years driven by electrification of the car fleet and heating (via heat pumps), but also by the need to produce hydrogen for energy storage.

Table 3 shows the same load as in Table 1. It also shows two scenarios for covering the load with renewable generation: In the first scenario, all renewable energy generation is increased by 118% (row 4). In the second scenario, all renewable energy generation is increased by 50%, except for offshore wind, which is increased by 678% (row 5). The relative variability of each renewable generation form is kept as in the past period studied. Both scenarios match total renewable generation with load, as average over 5 years.

Table 3: Scenarios for renewable generation matching consumption on average.

Residual load level	A. Average (GW)	B. Standard deviation (GW)	C. Largest instant shortfall (GW)	D. Largest cumulative shortfall (TWh)
1. Load	−56.2	9.7	−25.9	−44
4. Scenario: All renewables +118%*	0	22.4	−56.3	−68
5. Scenario: Offshore wind + 678%, other renewables +50%	0	23.2	−57.7	−43

*Numbering of rows is continued from Table 1.

The two different scenarios are shown to illustrate whether different ways of reaching renewable generation parity would have a major impact on the shortfalls. More offshore wind would reduce significantly the largest cumulative shortfall, but create slightly larger instant shortfalls. The numbers shown in columns C and D for both scenarios can be rounded for the purpose of further discussion: Germany must, on cold and calm winter evenings, be prepared to supply 60 GW of electricity not coming from renewables the way renewables have been used in the past. It must also be prepared to supply 70 TWh on similar criteria, over a period of 3 years, to make up for extended periods of low winds and high consumption. A detailed examination of the results also revealed that the cumulative shortfall could be as much as 40 TWh within a 12 months period.

Fig. 3 illustrates the scenario on row 4 of Table 3. The sloping curve represents the residual load in individual hours, which is 0 on average, since the scenario is designed to match generation with load on average. The largest negative load of −56.3 GW is found at the low right end. The negative residual load exceeds −40 GW in 1.4% of all hours.

At the other, upper left end, the largest residual excess in the scenario is 76 GW. This huge amount of surplus electricity would need to find useful applications that could in turn benefit Germany in times of shortfall.

Solutions are sought for meeting the shortfalls indicated on the right half of Fig. 3 and in columns C and D in Table 3. Some contributions may come from features that are inherent in Germany's current system, but these seem unlikely to reduce shortfalls by much more than they did in the recent past, as already reflected in Table 3. They may include:

- More targeted use of storable biomass fuels in times of large shortfalls;

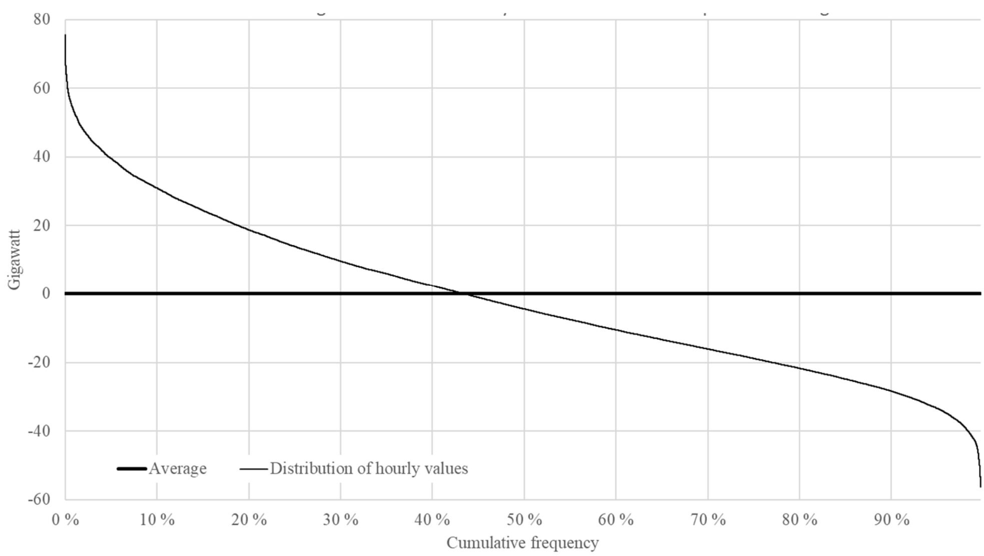

Figure 3: Residual load frequency in scenario with average renewable generation matching consumption in Germany and Luxembourg.

- Strategies by electricity users for shifting consumption to times of low prices;
- Cross-border trade responses to price variations driven by German load variations.

The potential solutions that can currently be identified for meeting the shortfalls by means in Germany involve energy storage in various forms, so implicitly moving electricity from the left side to the right side of Fig. 3. Energy storages include pumped hydro, batteries, hydrogen or ammonia via electrolysis, flywheels, and various ingenious uses of subsurface features. All significant forms of energy storage entail investment costs, operating costs and loss of energy in operations. Pumped hydro causes energy losses of 20%–35% of the regenerated electricity, depending on local conditions.

To match renewable generation with consumption when energy storage will require significant amounts of energy, Germany's renewable generation must increase to also allow for this energy requirement. This effect has not been incorporated in the analysis here. There will clearly to be a strong motivation for finding ways of avoiding the most expensive and ineffective energy storages as Germany further expands the renewable components of its electricity generation mix.

6 NORWEGIAN RESOURCES AND GERMAN LOAD VARIABILITY

The Norwegian power sector resources that can be considered relevant to address German challenges with load variability, are primarily:

- 87 TWh capacity for stored electricity potential in water reservoirs;
- Large electricity production primarily from hydropower;
- Good wind resources onshore and offshore, but challenged by environmental concerns and high costs;
- Power cable connections with Germany (1,400 MW) and Denmark (1,630 MW).

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The power cables between Denmark and Norway can be considered partly relevant because flows from Norway to Denmark (DK1) are often matched by simultaneous flows from Denmark (DK1) to Germany, and vice versa. In 2019–2022, an average of 6.1 TWh per year flowed from Norway to Denmark, and 2.1 TWh per year in the opposite direction. 54% of the flow from Norway to Denmark and 67% of the flow from Denmark to Norway were matched by simultaneous flow in the same direction between Denmark and Germany. At other times, power flowed either into Denmark (DK2) from both directions or out of Denmark in both directions, driven by a deficit or surplus of generation there. Denmark has a high portion of wind generation (55% during 2019–2022), which is significantly correlated with German wind generation (correlation coefficient 0.68 during 1 October 2018–31 March 2023). The effective capacity for moving electricity between Norway and Germany therefore varies between 1.4 and 3 GW in both directions.

That is not much compared to the German instant shortfalls sometimes approaching 60 GW, and even larger instant excesses, if Germany achieves renewable generation matching its consumption on average. So, Norway though the currently existing power cables cannot be a big contributor to meeting German instant shortfalls.

Its contribution can still be of significant value, because the trade flows and hydropower production in Norway can be shifted rapidly. The shifts usually do not entail any large energy loss or other inefficiency, as the production held back translates into water in reservoirs for later use. Germany's pumped hydro storage provides another option for quick responses to surging residual loads or excesses, but is of limited capacity as reviewed in Section 5.

The other measure of missing electricity in Germany, cumulative shortfall, can approach 70 TWh if Germany acquires renewable generation matching its consumption on average. Based on historical data, this would happen over a period of three years, but the shortfall could be as much as 40 TWh in a 12 month period. The cables can in theory move 12 TWh from Norway to Germany over such a period, which would be a significant contribution to meeting a 40 TWh cumulative shortfall. In practice, the amount of power transferred will be less, for two reasons: First, constraints in Norway's effective reservoir availability due to the need to secure winter power supply as reviewed in Section 3. Second, even in an extended period of low wind and power generation that creates the cumulative shortfall, there will be short periods of excess, where power is likely to flow in the opposite direction, thus reducing the cumulative net export from Norway.

7 IMPLICATIONS FOR ELECTRICITY COSTS IN NORWAY

As a national economy, Norway has profited from high electricity prices. They generated a trade surplus of €5.3 billion in 2021 and 2022 combined from Norway's trade with Britain, the Netherlands, Germany and Denmark. This can be disaggregated as €4.6 billion from net exports and €0.7 billion as a margin on balanced trade, measured at the prices in the Norwegian bidding zone (NO2) where those cables connect to the Norwegian grid. The positive margin on balanced trade arises because Norway has been in a position to import electricity at lower prices than it has exported, made possible by the flexibility offered by its water reservoirs. For countries on the continent the situation is reverse: They export to Norway when their prices are low, and import when prices are higher. For these countries, the flexibility required to cover variations in the net load comes at a high cost.

For any year, the trade surplus achieved by Norway, measured at prices in Norway, is less than the corresponding trade deficit of its trading partners from the same trade. The difference becomes income for the grid companies owning the power cables, and is used for covering the costs of the cables.

The profits achieved by Norway as a national economy from trade and high prices do not prevent citizens of the country from perceiving the same as a deprivation. High electricity prices in 2021–2022 have generated a transfer of money from electricity users to the Norwegian state and other public entities, which include most power producing companies. A compensation scheme protects households (and, to a limited extent, businesses) from very high electricity prices, still leaving households with significantly higher costs per kWh than in previous years. The arrangements that most Norwegian households and business have for purchasing electricity, link their effective costs directly to the trade prices for electricity on the Nordpool electricity exchange (www.nordpoolgroup.com). Hence there is a strong public focus on market prices for electricity, and a popular as well as political desire to keep them low.

Domestic electricity prices in Norway are evidently influenced by those on the European continent. The correlation of hourly prices during 2015–2022 of NO2 against German prices has been 0.93, with a slope of 0.82. The influence is strongest in the southernmost Norwegian bidding zone, NO2, which has all the direct cable links to the European continent and Britain, and often has higher electricity prices than the rest of Norway. The extent to which this influence has been strengthened by the latest cables with Germany and Britain is less clear, as there was a significant correlation of prices also before the advent of those cables. The price difference between Germany and Norway (NO2) since that cable started operating from 2021 has varied strongly from one month to the other, and was no less on average in 2021 and 2022 than it had been in earlier years. (The average price for NO2 was €22/MWh lower than in Germany in 2021, and €24/MWh lower in 2022. The difference in individual months varied from +15 to −60 €/MWh.)

Norwegian electricity prices fluctuated less than the German ones, having lower standard deviation during 2015–2022. (Within-year standard deviations of hourly prices averaged €27/MWh in NO2 and €39/MWh in Germany during 2015–2022.) In 61% of all hours, the NO2 price change from 24 hours earlier was in the same direction as the German price change, but by a smaller amount. This again indicates that the larger continental electricity markets drive price changes in Norway, but moderated by the more flexible Norwegian system.

During each hour, the trade flow between Germany and Norway is driven directly by the price difference between them. Indirectly, the causality is different: Trade flows need to reflect differences between generation and consumption, which therefore drive the relative price formation between bidding zones. It is therefore unsurprising that Norwegian prices are lower relative to German ones in years when Norway has large net exports. The correlation of yearly averages during 2015–2022 was 0.73, with a slope of €11.33/MWh lower NO2 price relative to the German price for each 1 GW of extra net exports from NO2.

Norway therefore can influence its electricity prices to some extent, notably the extent to which they will be higher or lower than on the European continent, by maintaining a positive balance of electricity generation over consumption. Large price movements are driven by continental electricity markets, but moderated by the flexibility of Norway's system.

Norway's authorities have means at their disposal to modify the impacts of high prices on consumers more than they have done, and to do so without much distortion of incentives for economising on power use. Consumers' and businesses cost of electricity are determined not only by trade prices, but also by taxes, distribution costs and other components of invoiced costs. These have long been relatively low in Norway compared to many other countries. It would also be possible to create arrangements by which the incremental profits accruing to the state from particularly high prices would be systematically redirected to citizens and businesses, and not necessarily in the form of incentives-distorting intervention in prices.

8 OPTIONS FOR INCREASING NORWAY'S AVAILABLE FLEXIBILIY

8.1 Trade-off between short-term and long-term flexibility

There is a trade-off between using the flexibility that the Norwegian system can provide, between meeting short term and long term deficiencies, i.e. instant and cumulative shortfalls. If the system is used for supplying a maximum rate of electricity to Germany over an extended period, there is no additional capacity for supplying additional electricity during brief period of exceptionally high residual load. The flexibility for providing the latter is highest if flows on the cables are balanced in the longer term.

To maintain a significant capacity for Norway to vary the flow of electricity to and from Germany in the short term, Germany should avoid becoming dependent on importing large amounts of electricity from Norway in the longer term, even if it would be possible.

8.2 Increase non-hydro winter generation?

Large reservoir capacities are needed in Norway to maintain high generation through winter, when inflow of water into the hydropower system is low. The need to reserve reservoir capacity for this purpose would be reduced if Norway acquired more power generation in winter. This would especially be the case if there would be more added power generation in winter than in the rest of the year, and the added generation would be matched by consumption evenly spread over the year.

Wind power fits this requirement. In the winters 2010/11 to 2021/22, wind generation was on average 57% higher in the months October to March than during the remaining months of the previous and following years. This was onshore wind only, as Norway did not have significant offshore wind in the period. ENTSO-E Data from Germany and Denmark (DK1) indicate that offshore wind shows somewhat less but still quite large seasonality, with high winter generation.

A scenario in which Norway significantly increases wind production would therefore lessen reservoir constraints on the longer-term flexibility of power supply that Norway can provide to the rest of Europe. This would result if the annual increase in generation is matched by increases in consumption that is spread evenly over the year, which is typically the case for industrial applications.

Increasing Norwegian wind generation meets substantial obstacles. Onshore, this is due to local and regional environmental concerns. Wind developments in Norway have tended to take place at locations previously not much affected by human activity. Wind developments are also in conflict with traditional activities by reindeer herders of the Sami population, which tend to take place across large areas in northern and central Norway.

The Norwegian Government has significant aspirations for offshore wind, aiming for 30 GW installed capacity by 2040. As technologies currently stand, wind development in Norway will be more costly than in other European offshore areas. This is partly due to distances, but mainly to sea depth and bottom conditions that are not suited to bottom fixed wind turbines of the kind in common use elsewhere. The authorities and several firms pursue development of floating wind installations, building on Norway's large experience with offshore petroleum installations. Recent indications are that floating offshore wind at acceptable cost remains an uncertain and distant goal. The Norwegian state will be prepared to support and subsidize the development of floating wind in early stages, if it is recognized as having a clear potential for unsubsidized economic viability in the longer term. A test of this will be a competitive licensing round, ongoing in 2023, for offshore wind development in two areas outside southern Norway [12].

8.3 Increase the transmission capacity between Germany and Norway?

The existing cable between Germany and Norway, named Nordlink, had an investment cost of €1.8 billion and started regular operations in 2021. Investors were grid operators TenneT and Statnett. An additional cable of 1,400 MW between Germany and Norway has been considered but the project was discontinued before reaching investment decision.

An additional cable, and possibly further cables beyond that, would require not only the investment cost in the cable itself but also investments in the Norwegian grid and generation systems to enable a high utilization of the capabilities of the cable. This kind of capacity therefore has increasing marginal cost.

It also has decreasing marginal benefits. One cable can transfer +/− 12 TWh of electricity per year if used continuously in one direction only. This is significant in terms of meeting Germany's potential cumulative shortfall, indicated earlier to be around 70 TWh in case of renewable generating matching consumption on average. It is also significant in terms of exhausting the potential flexibility that Norwegian reservoirs can provide. This indicates that the profitable utilization of such cables will increasingly come up against limitations on both ends if the total capacity is increased.

One or more additional cables would make potential contributions to supplying Germany's residual loads. But with the residual load potentially varying with +/− 60 GW in a German system in which renewable generation matches consumption on average, cables providing +/− 1.4 GW each would need to implausibly numerous in to make a large contribution. So Germany will need other strategies than cables to Norway for covering its variations in instant residual loads.

The one cable that was planned and not decided, may be reconsidered at some point and possibly be built, especially if Norway establishes more wind generation. Additional cables between Norway and the continent will be harder to justify. The research project HydroConnect, referred in Section 1, is undertaking in-depth studies of the potential for stronger electricity linkages between Norway and the European continent.

9 CONCLUSIONS

In a future scenario in which Germany's renewable power generation increases to match its recent level of consumption on average, Germany must be prepared to supply up to 60 GW of instant power and up to 70 TWh of cumulative power over 3 years (of which 40 TWh over 12 months) from sources other than renewable energies the way these are currently utilized. Norway will be able to supply only a small part of such instant power but a larger part of the cumulative power over time. This would not allow Germany (and similarly other European continental nations) to reduce their need for back-up generation capacity to any large extent, but would significantly reduce the amount of electricity needed from relatively inefficient backup generation and energy storage.

The numbers cited above relate to Germany's recent level of electricity consumption, and do not incorporate any effect of anticipated increases in consumption that will result from the energy transition. Such added consumption will have different patterns of variability and flexibility than the current consumption.

Norway's capacity for offering such electricity trade will be augmented if more wind generation capacity is established in Norway. Assuming that Norway's electricity trade with Germany will be largely balanced in energy terms in the longer run, such exchange of electricity will generate significant net revenues for Norway while reducing Germany's costs of balancing its electricity supply between times of excess and shortfalls in its residual load.

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