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Buffering volatility: A study on the limits of Germany's energy revolution☆

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ABSTRACT

Squaring hourly demand and wind-solar production data for Germany and a number of neighbouring countries with the results of the EU's ESTORAGE project, this paper studies the limits of Germany's energy revolution in view of the volatility of wind and solar power. In addition to pumped storage, it considers double-structure buffering, demand management, Norwegian hydro-dam buffering and international diversification via grid expansion. If Germany operated in autarchy and tried to handle the volatility of wind-solar production without using stores while replacing all nuclear and fossil fuel in power production, on average 61%, and at the margin 94%, of wind-solar production would have to be wasted, given the current level of other renewables. To avoid any waste, the wind-solar market share in an autarchic solution must not be expanded to more than 30%. By using Norway's hydro plants the share could be expanded to 36%. If Norway were to build all the pumped-storage plants the ESTORAGE study deems feasible, Germany's wind-solar market share could be expanded by another 24 percentage points to about 60%, which corresponds to 48% of the combined German and Norwegian markets. Additionally expanding the market to Switzerland, Austria and Denmark and building the maximal number of pumped stores would increase the combined wind-solar market share for all five countries to nearly 50%.

1. Introduction: Germany's energy revolution

With its *Energiewende* Germany is planning a true energy revolution,[1] dramatically boosting the market share of wind and solar energy in the production of electric power, crowding out fossil energy in general, and exiting nuclear energy. This paper studies the challenges posed by this endeavour, focusing on the difficulties of coping with the enormous volatility of wind and solar energy.

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[1] For discussions of the feasibility, see Nitsch et al. (2010), Klaus et al. (2010), and Sachverständigenrat für Umweltfragen (2011). For a discussion of the economic aspects, see Edenhofer et al. (2013).

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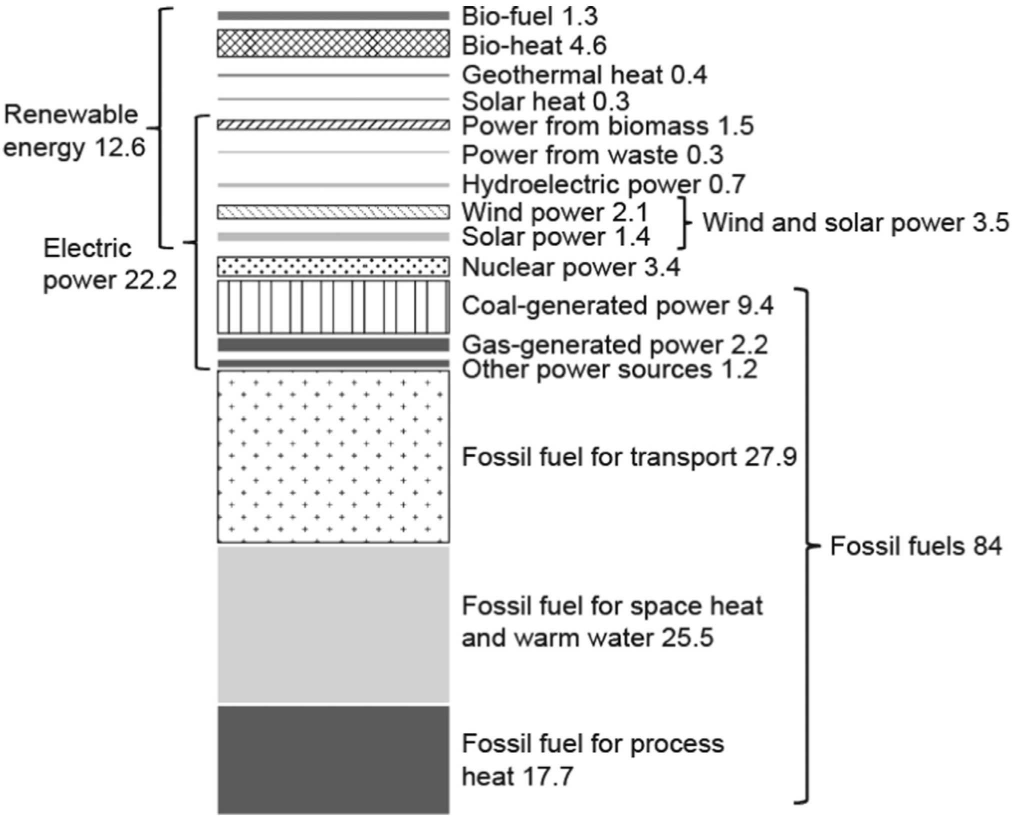

Fig. 1. Germany's final energy production (2014, %).
Calculations based on: Arbeitsgemeinschaft Energiebilanzen (2015, 2016), Arbeitsgemeinschaft Energiebilanzen, Bruttostromerzeugung in Deutschland nach Energieträgern, http://www.ag-energiebilanzen.de/index.php?article_id=29&fileName=20160128_brd_stromerzeugung1990-2015.pdf.
Note: The percentages shown relate to Germany's final energy production of 2450.2 TWh by source. Final energy production is defined as aggregate production minus the energy sector's own consumption.

Arguably, the most prominent and promising strategies to buffer volatility involve pumped-storage plants, demand management, double structures retaining conventional plants as back-ups as well as grid expansion to other countries including Norway's hydro plant facilities. This paper discusses these options, squaring hourly production and consumption data for Germany and a number of neighbouring countries with new data on the geological and economic possibilities for the construction of pumped-storage stemming from the EU's ESTORAGE project. According to the EU Commission, pumped storage plants "offer a new era of smarter energy management" that would help Europe to move to green energy and fight climate change.[2]

Germany's green energy revolution has been going on for two decades, but accelerated substantially after the 2011 Fukushima accident, as Germany reacted with the decision to abandon all of its 17 nuclear power stations, which at that time accounted for a good fifth of the country's production of electric power. By the end of 2015, nine nuclear plants were shut down, with a phase-out of the remaining plants scheduled for 2022.

Germany also wants to phase out fossil fuel. In the Kyoto agreement the EU committed to an 8% reduction (United Nations, 1998) in CO_2 emissions, and in the subsequent EU negotiations it agreed to contribute by cutting its own emissions by 21% (European Communities, 2002) by 2012. Moreover, Germany announced that it will reduce its emissions by a further 19 percentage points by 2020, so as to achieve an overall reduction of 40% versus 1990.[3] Following the EU decisions, it intends to cut emissions by 80% by 2050.[4]

The double exit from nuclear and fossil energy is ambitious. The dimensions of this task are illustrated in Fig. 1, which offers an overview of Germany's entire final energy structure by sources and final uses of energy in 2014 (which happens to be very similar to that of the OECD as a whole).

The figure shows that in 2014, with a share in final energy production of 3.5%, wind and solar power contributed about as much energy as the remaining nuclear power plants, which accounted for 3.4%. Thus, a near doubling of Germany's

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[2] See DNV GL (2015) and European Commission (2016).

[3] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (2014).

[4] European Commission (2011).

current wind and solar plants compared to 2014 would make it possible to replace all of the country's remaining nuclear power plants, which seems like a feasible goal.[5] This, however, would not yet constitute a contribution towards curbing the emission of fossil fuels, which account for 84% of Germany's entire final energy production and result largely from the production of heat for homes and for processing purposes, as well as from transportation. A full decarbonisation strategy, the discussion of which goes beyond the scope of this paper, would involve much more than just producing more electricity from wind and solar energy.[6]

The reader should note in this context that the percentages mentioned refer to the entire final energy production rather than electricity production alone, which represents only one fifth of the total. Thus, while wind and solar power constitute 3.5% of the total final energy production, they account for about 16% of electricity production, as mentioned above. If we add the other green power sources shown in Fig. 1, which account for nearly 11% of electric power, green power boasts a share of 27.0% of total final electric energy production. Other things equal, this share would rise to around 42% if all nuclear energy were to be replaced with wind and solar energy.

After replacing nuclear power, Germany's next logical endeavour would be to replace electric power generation from coal, natural gas and other fossil sources such as oil products and non-renewable fossil waste, which account for a combined 13% of total final energy consumption, or 58% of Germany's current electric power generation.

2. Smoothing wind and solar power

Germany's landscape has been transformed by wind and solar plants in recent years. In 2014, a total of around 24,000 wind turbines were scattered across the country, predominantly in northern Germany. These turbines are so frequent in the north that there is hardly any place in nature where the blinking red warning lights of the generators, typically with an overall height of 150 to 250 m, cannot be seen on the horizon at night. Moreover, the roofs of private dwellings all over Germany, primarily those of farm buildings, are often covered with solar panels (while land space covered with such panels is rare, given that ground panels are no longer permitted).

The policy tool with which Germany achieved this astounding conversion of its landscape is feed-in tariffs. These tariffs are fixed prices for green electricity, guaranteed for twenty years, combined with a priority right to deliver the power to the grid prior to conventional power sources. Grid companies are forced to connect even the most remote wind generators and solar panels free-of-charge.[7] Instead of following the law of one price, the German authorities have developed a complicated set of alternative prices differentiated by calendar time of instalment and types of installation. The prices have come down over time. In 2015, the prices for new installations were 8.90 cents per kWh for wind and 9.23 cents per kWh for solar power.[8] As a rule, the less efficient the appliances are, the higher are the prices, so as to give all technologies a "fair" chance.[9]

While Germany's achievements are impressive, there is a fundamental problem relating to the volatility of wind and solar power. As promising as the aggregate statistics that add and relate energy from different sources may be, they overlook the inherent quality differences among these sources in terms of continuity and adjustability of supply.

Fig. 2 shows hourly data on all German wind and solar electricity fed into the grid in 2014. The highly volatile curves give the flow of produced electricity in terms of GW. They have been trend-adjusted to eliminate the underlying growth in installed plants during the year. On average, 24,256 wind power plants were installed, each with a production capacity of 1481 kW and 1.5 million solar power plants each with a production capacity of 26 kW.

While the installed wind power production capacity was 35.92 GW, average production was 5.85 GW, just 16.3% of capacity, and secured production which was available in 99.5% of the hours, was 0.13 GW, or 4 per mille of capacity. At 37.34 GW, the installed solar capacity was nearly the same as in the case of wind power. However, the average production was only 3.7 GW, which is 9.9% of capacity, and, of course, secured production was zero. On average, a wind power plant in Germany produced 241.4 kW, and a solar power plant 2.55 kW.

In order to make green power usable despite its volatility, buffers are needed. The following paragraphs first study a storage strategy, assuming ideal stores that can be filled and emptied without friction. Later in this paper more realistic buffering strategies will be studied, based on storage with frictions and double structures as well as international grid expansions. What comes closest to ideal storage is pumped-storage plants (PSP), of which Germany currently has 35. When there is an excess supply of energy, water is pumped from a lower lake or river to an upper storage lake, and when additional energy is needed it is generated by releasing water from the upper lake. On average, a German pumped-storage plant has a volume of 1.077 GWh, and the total energy volume of all pumped-storage plants is 0.038 TWh. Unfortunately, Germany's geological conditions do not allow for much more volume to be built. According to the ESTORAGE project, just one

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[5] See Kunz and Weigt (2014) who, in their ex-post evaluation of the nuclear phase-out, come to a similar conclusion.

[6] For an extensive analysis of Germany's options, see Hillebrandt et al. (2015).

[7] According to Ferroni and Hopkirk (2016), the investment necessary to connect remote locations consume so much energy that solar panels become energy sinks instead of serving as energy sources. Cf. also Trainer (2014).

[8] This was 5.74 or 6.07 cents higher, respectively, than the wholesale prices for electric power. See Bundesministerium für Wirtschaft und Energie (2014), and European Energy Exchange AG (2016). Note, however, that the wholesale prices themselves may have been depressed by the merit order effect resulting from the zero marginal cost of wind-solar power, once the plants are installed. It is debatable how large this effect is. After all, the wholesale price in France, for example, exceeded the German wholesale price by less than 0.05 cents per kWh. See European Energy Exchange AG (2016).

[9] For a critical assessment of price differentiation in general, see, for example, Karp and Liu (2002).

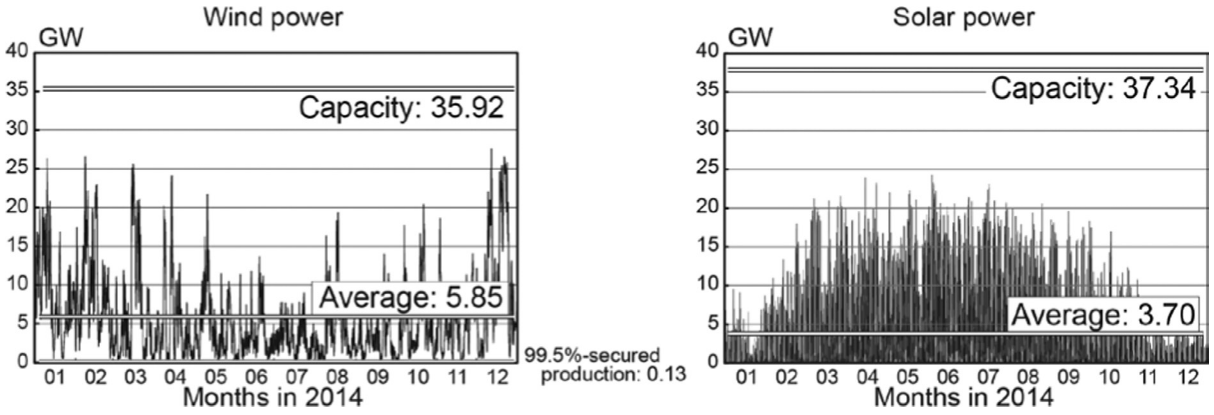

Fig. 2. Wind and solar power in Germany 2014 (hourly data).

Sources: Amprion, http://www.amprion.net/photovoltaikeinspeisung, Tennet, http://www.tennettso.de/site/Transparenz/veroeffentlichungen/netzkennzahlen/tatsaechliche-und-prognostizierte-solarenergieeinspeisung_land?lang=de_DE, Transnet BW, https://www.transnetbw.de/de/kennzahlen/erneuerbare-energien/fotovoltaik, 50 Hertz, http://www.50Hz.com/de/Kennzahlen/Photovoltaik/Hochrechnung, Bundesverband Solarwirtschaft, https://www.solarwirtschaft.de/fileadmin/media/pdf/2016_3_BSW_Solar_Faktenblatt_Photovoltaik.pdf, Bundesministerium für Wirtschaft und Energie, http://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2015.pdf?__blob=publicationFile&v=6.

Note: The data have been trend-adjusted to compensate for the slight growth in plant capacity over the year without changing the average. In 2014, there were on average 24,256 wind power plants and about 1.5 million solar power plants installed in Germany.

Source: Amprion, http://www.amprion.net/windenergieeinspeisung, Tennet, http://www.tennettso.de/site/Transparenz/veroeffentlichungen/netzkennzahlen/tatsaechliche-und-prognostizierte-windenergieeinspeisung, Transnet BW, https://www.transnetbw.de/de/kennzahlen/erneuerbare-energien/windenergie?activeTab=table&app=wind, 50 Hertz, http://www.50⟨11:hsp 0:sp="0.2"⟩⟨/11:hsp⟩Hz.com/de/Kennzahlen/Windenergie/Hochrechnung, Bundesverband Windenergie, https://www.wind-energie.de/infocenter/statistiken/deutschland/installierte-windenergieleistung-deutschland.

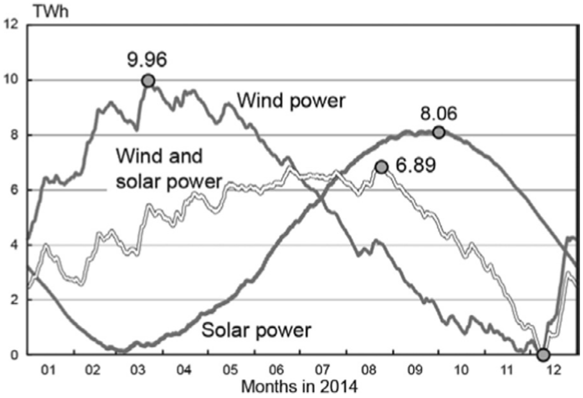

Fig. 3. Storage needs for wind and solar power, separately and jointly (German hourly data 2014).

big additional pumped-storage plant with a volume of 0.007 TWh could reasonably be constructed in Germany in addition to its present facilities, bringing Germany's total storage volume to 0.045 TWh.[10]

Fig. 3 shows the outcome of a thought experiment in which the actual, volatile production of wind and solar energy is flowing into a store, while the steady outflow equals the average inflow, i.e. the 5.85 GW or 3.7 GW, respectively, shown in Fig. 2. The assumption of a steady, non-volatile outflow is made here and in the next few pages to ensure that wind and solar power is able to replace conventional base load power sources without imposing additional buffering needs on them or other conventional sources, which would reduce their degree of capacity utilization and profitability. The three curves shown in the figure depict the volume of stored energy in terms of TWh at each point in time during the year for wind power, for solar power and for the two weather-dependent power flows together. By construction, the final volume by the end of the year is equal to the initial volume, both being chosen such that the year's minimum is zero. The highest points of the curves give the storage volume necessary to smooth Germany's respective wind, solar and joint wind-solar power production in 2014.

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[10] See DNV GL (2015), p. 40.

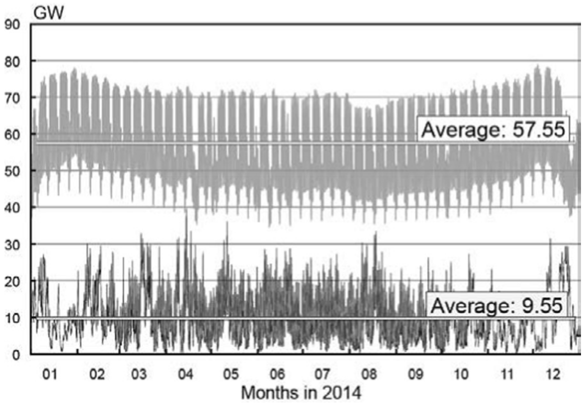

Fig. 4. Wind and solar power (lower line) compared to aggregate gross power consumption (upper line) (German hourly data 2014).
Note: Trend-adjusted data for wind and solar production. The Euro Network consumption data refer to consumption before distribution losses. They are not fully compatible with the Arbeitsgemeinschaft Energiebilanzen data used in Figure 1 and result in a slightly higher share of wind and solar energy (16.6% instead of the 16% mentioned there). Cf. https://www.entsoe.eu/Documents/Publications/Statistics/20150531_MS_guidelines_public.pdf.
Source: European Network of Transmission System Operators for Electricity, https://www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month, as well as sources given for Figure 2.

Obviously the wind store is fullest at 9.96 TWh, equivalent to 9243 pumped-storage devices of the German variety, or 264 times the country's actual pumped-storage volume. The solar storage curve in turn peaks at a storage volume of 8.06 TWh or 7486 pumped-storage plants.

However, separate stores for wind and solar energy are not advisable as wind and solar power are negatively correlated. While wind is strong in the winter, from December to March, solar power reaches its peak in the summer months. The wind store is fullest in the second half of March (22 March 2014), and the solar store has its maximum content in early October (4 October 2014), about half a year later.

The hollow curve in Fig. 3 shows the aggregate of the wind and solar storage curves. It was calculated by adding the wind and solar storage volumes and abolishing unnecessary storage space such that the storage volume would again be zero at the lowest stock of energy stored, which is the case in early December. The highest storage volume, which would be reached in the second half of August, gives the necessary storage size, at 6.89 TWh or 6395 pumped-storage plants. It is remarkable that this required storage volume is not only smaller than the sum of the separate required storage volumes, but is even smaller than the storage requirement for each of the two power sources considered individually.[11]

3. Volatile demand

The next step in the analysis involves taking the volatility of power consumption (the load) into account. As a strategy of buffering wind and solar power implies huge storage needs, there is some hope that recognition of volatile consumption may further lower storage requirements. After all, it is often argued that green electricity may help to "break the consumption peaks" in Germany, as sun power is positively correlated with consumption over the course of the day. Fig. 4 looks into this issue.

The figure shows the aggregate hourly electricity consumption gross of distribution losses in addition to the hourly joint production of wind and solar energy. Obviously it is also very volatile, even more volatile than the production of wind and solar power, but indeed the series are positively correlated.[12]

Fig. 5 informs about the storage need resulting from the attempt to smooth both supply and demand in the German market. The hollow curve repeats the wind-solar storage curve of Fig. 3, the grey curve shows the storage curve for demand smoothing alone, and the solid curve shows the storage curve for supply and demand taken together.

The thought experiment underlying the demand-storage curve is that volatile demand is serviced from a store, which is replenished with a constant inflow equal to the average outflow. By construction, this strategy implies that the store's end-of-year energy stock is the same as the stock at the beginning of the year. Again, the required storage volume is the

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[11] Complementary information can be gained by taking a look at statistical data. While the variance of hourly wind power production in 2014 was $2.95*10^{19}$ W^2h^2, the variance of the solar power production was $3.06*10^{19}$ W^2h^2, and the variance of wind and solar production together was $5.07*10^{19}$ W^2h^2. As the variance of the sum of wind and solar power is less than the sum of the respective variances, the correlation between the variables is negative. In fact, the correlation coefficient between wind and solar power is -0.16. It is worth noting, however, that statistical information based on the sum of squared deviations from a mean is only a rather loose and indirect indicator of storage needs, as the temporary variance in periods when the store is neither full nor empty is irrelevant for the maximum storage need. As Fig. 3 shows, the storage need for wind and solar power taken together is less than the required storage volume for each of these power sources alone, despite the fact that the combined variance is higher than each of the single variances.

[12] The correlation coefficient is +0.30.

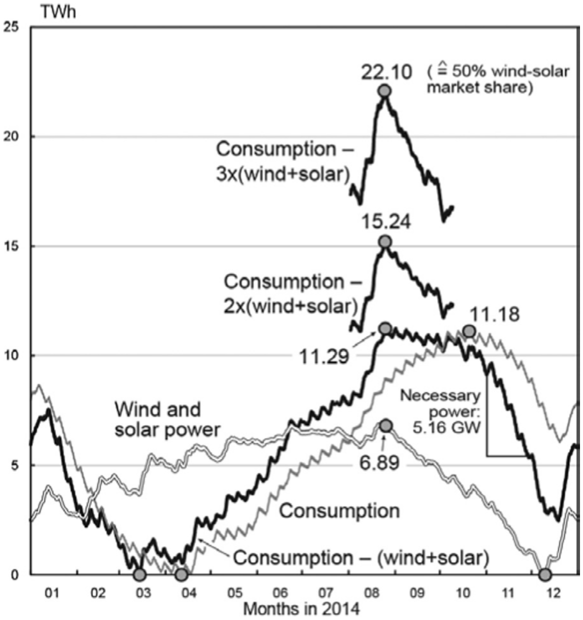

Fig. 5. Buffering wind power, solar power and power demand with storage devices (based on German hourly data of 2014).

store's maximum volume resulting from an initial level that empties the store for at least one hour during the year. The calculations show that the lowest storage volume (zero) is reached by 11 April and volume peaks on 20 October at 11.18 TWh or 10,379 pumped-storage plants of the German variety.

By contrast, the thought experiment behind the (solid) curve, smoothing both supply and demand, is that all conventional plants (including coal, gas, nuclear, biomass, hydro and waste etc., see Fig. 1) produce a constant flow of energy large enough to cover the average annual difference between volatile consumption and volatile wind-solar production. This constant flow from conventional plants is assumed to be equal to their actual average 2014 production, which stood at 48.00 GW. Otherwise, the calculations follow the same logic as above. They show that the combined store is empty by mid-March and full in late August (25 August), which is nearly the date at which the store for smoothing wind and solar energy alone would be full (24 August). The storage volume at the latter date, which is 11.29 TWh, is the necessary storage volume. This volume is much higher than the volume that turned out to be necessary to buffer solar and wind production (6.89 TWh), as was shown in Fig. 3, but only a little higher than the volume needed to smooth consumption alone, which is 11.18 TWh. Thus, the integration of wind and solar power at their current volumes into the German grid would not actually require substantially more storage volume than smoothing demand alone.

It is important to note, however, that this is just a snapshot result, as Germany plans to rapidly expand its wind and solar power and build many more wind and solar plants in the future. Given that all geographical regions that could possibly be distinguished by their climate conditions have already been scattered with wind turbines and solar panels, it is assumed that the power produced by the new plants will be perfectly correlated with the power generated by the existing ones.[13] Thus, an expansion of production will proportionally expand the production curve shown in Fig. 4, including its mean and standard deviation. As illustrated by the two peaks above the point of maximum storage, a doubling and trebling of Germany's current wind and solar plants at identical locations would strongly increase the storage needs way beyond the 2014 figures to 15.24 TWh and 22.10 TWh, respectively, which would be equivalent to 14,153 and 20,517 pumped-storage plants of the average German size. Trebling Germany's current wind and solar production would imply that half (49.80%) of its electric power supply was generated by wind and solar power.

To take this thought experiment to an extreme, let us assume that the wind-solar market share is expanded to 100%, while no other power plants are available. In this case, a storage capacity of 42.93 TWh or 39,854 pumped-storage plants of the average German size would be needed. This is 1139 times the country's current pumped-storage volume. While the average wind-solar production would be equal to Germany's consumption, the capacity of the respective plants would be about eight times the average consumption.

Sometimes the size of storage devices is described as a power flow measured in gigawatts, rather than volume or stock measured in gigawatt hours. Indeed, the question is not only how much energy can be stored, but also how quickly it

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[13] Indeed, as Ahlborn (2015) shows, the coefficient of variation of German wind power has not exhibited a declining trend in recent years which would have indicated at least some degree of stochastic independence.

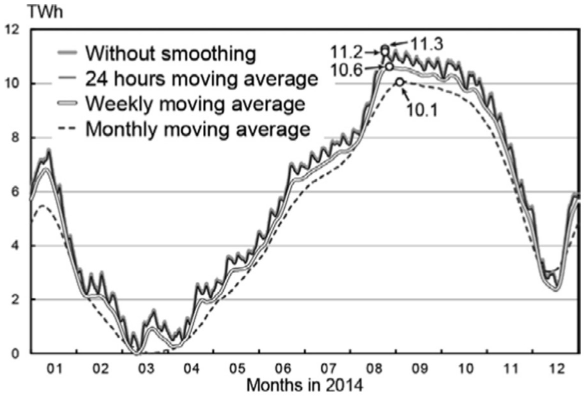

Fig. 6. Absorbing high frequencies with demand management (hourly data Germany 2014).

can be released. Could pumped-storage devices face an additional constraint in this respect?[14] The answer is given by the triangular slope measure in the right-hand region of Fig. 5, which refers to the situation in 2014. The month with the steepest negative slope in the diagram is November. Here, the store's energy volume falls by 3.72 TWh in the month's 720 hours, which implies a necessary withdrawal power or production capacity of around 5.16 GW. As Germany's existing 35 pumped-storage plants have a joint production capacity of 6.57 GW, this obviously would not be a binding constraint. However, if all of the pumped stores were emptied simultaneously so as to meet the 5.16 GW power demand, they would last for just 7 hours and 18 minutes. This shows that only the volume, or "labour" to use the physical term, and not "power", is a binding constraint.

4. Demand management

The public debate tends to focus on demand management and smart grids that would help adjust electricity demand to volatile supply. Peak load pricing could help increase the correlation between supply and demand so as to reduce storage requirements. Indeed, there is a lot of potential flexibility on the demand side. Dishwashers and washing machines, as well as tumble dryers, could be programmed to operate during periods of ample supply and at correspondingly low prices. Refrigerators and freezers have a certain inertia and internal storage potential, so they do not need a power connection all the time. Hot water boilers could be heated with electric current when available and store the heat for a couple of days. Similarly, brick houses with substantial temperature inertia could be heated and cooled at times when cheap power is available. Pre-cooking meals and shifting power-consuming activities also implies greater flexibility. Even industries could shift non-frequent, but power consuming activities to times of high supply.

Unfortunately, however, closer inspection of Fig. 5 reveals that the storage requirement results from long-term seasonal fluctuations rather than short-term frequencies of a few hours or days. It would be necessary to store energy from August to the winter months through March, in other words for nearly 7 months, to address the volatility issue. Obviously, the freezer would not keep cold for half a year. Neither would it be enough to heat a house at intervals that are months apart, particularly not in summer when everything is warm anyway. Storing dirty dishes and laundry for months before they would be washed is theoretically possible, but that would require unreasonably large stocks of dishes and clothes.

To assess the extent to which demand management, which absorbs the high frequencies, could possibly contribute to reducing storage space, the combined storage curve of Fig. 5 has been recalculated after smoothing the difference between consumption and green (wind and solar) production with moving averages stretching over a day, a week or a month. This thought experiment is extreme in that it assumes a complete demand management within the time periods considered, adjusting demand perfectly to volatile wind-solar supply, to a far greater extent than would ever be possible in reality. The results are shown in Fig. 6.

Obviously, short-term demand management would hardly affect storage requirements. While a storage capacity of 11.29 TWh would be necessary without demand management, intra-day demand management would only reduce the storage requirement by 0.9% to 11.19 TWh, intra-week management by 5.9% to 10.62 TWh and intra-month management by 11.0% to 10.05 TWh. Thus, instead of 10,478 ideal pumped-storage plants, 9332 would be needed if consumption were reallocated within a month so as to coincide with green production peaks. This is still an enormous quantity compared to the 35 pumped-storage plants that exist in Germany.

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[14] For an analysis of the storage problem based on power needs, see Hack et al. (2014).

5. The double-structure strategy

Given the difficulties related to storage strategies and the limited potential of demand management, the reader may wonder how Germany manages to integrate its wind and solar power into its power supply. After all, the fluctuations are already present and storage plants have a miniscule volume relative to what would be needed. The answer is that Germany uses its existing fossil fuel plants and a few hydro and bio-energy plants to cushion the shocks resulting from inserting wind and solar energy into the grid (cf. Fig. 1).[15] In fact, the difference between the consumption and production curves in Fig. 4 is being offset primarily by conventional production in Germany and to some extent by international trade, a topic that will be dealt with later. When the wind blows and/or the sun is shining, substantial shares of the energy production come from German wind and solar energy, while conventional plants produce at a reduced pace or stand still. When there is no wind and sunshine, by contrast, conventional plants are used to fill the energy gaps and produce as much as they did before the wind and solar plants became available.

Gas power plants are most useful for buffering short-term fluctuations, but as these plants produce rather expensive electricity, most of the buffering is done by hard coal power plants. It is true that such plants cannot react as quickly as gas plants to fluctuating demands. Intra-day fluctuations are very difficult to handle. However, as the production of these plants can be doubled or cut in half within a few hours, and even a cold start does not take more than a day or two, the degree of flexibility offered is enough to cover most of the seasonal needs described in Figs. 5 and 6. Thus coal and methane stores that are refilled from mines and natural sites serve as principal buffers for German wind and solar energy.

To some extent even lignite plants and nuclear power plants are used to buffer volatility. In the case of lignite plants, a couple of days are required for a cautious shut down and re-start to avoid damage to the steam boilers. Moreover, while nuclear plants require days for a stop and a subsequent cold start, their output can be reduced to 50% within minutes, an option which has been rarely used due to safety considerations.[16]

While the German buffering strategy works, it is expensive, as it involves double structures with double fixed costs. On the one hand, it has undermined the profitability of conventional power plants, as it reduced their running hours and hence capacity utilization. This has not only made existing plants unprofitable,[17] but has even threatened the existence of huge power companies like Eon or RWE. On the other hand, the double-structure strategy has strongly increased the price of electric energy in Germany. In the first half of 2016, German electricity cost 29.69 cents per kWh for final household consumers, compared to merely 16.85 cents in France.[18]

The high cost of electric power partly results from the differing wholesale prices in Germany and France, and partly from taxes and a feed-in surcharge for green energy. The network companies have to pay the green producers the publicly-administered prices, but when these prices exceed the wholesale price at the market, the excess is generally imposed as a surcharge on consumers, with a few exceptions for energy-intensive firms. The feed-in surcharge increased from 0.19 cent per kWh in 2000 to 6.35 cent in 2016, which was equivalent to a total subsidy of 24 billion euros.[19] To put this figure into perspective, this represents about a hundred times the annual budget of government-financed Max-Planck Institute in Greifswald which runs an experimental nuclear fusion reactor, the Stellerator.

While the German double-structure strategy aims at contributing to the solution of a worldwide public-goods problem, it is uneconomical from a national point of view. The reason is that, without taking ecological considerations into account, wind and solar plants pay off if, and only if, their *average* cost is below the *marginal* cost of producing electricity from fossil fuels. Given that conventional plants are needed as buffers, their fixed costs cannot be spared. It is only their running hours, i.e., the marginal production costs including the direct energy cost that can be reduced by wind and solar power to the extent that this power is available. In 2016, the marginal cost of producing electricity from lignite was about 0.6 cents per kWh, and 2 cents from hard coal. Adding 0.8 cents per kWh or 0.7 cents per kWh, respectively, for the emission rights at 2015 average prices (7.5 euros per ton of CO_2) gives a marginal cost of 1.4 cents per kWh for lignite and 2.7 cents per kWh for hard coal.[20] By contrast, the feed-in tariffs for electricity from new wind and solar plants, which are presumably just large enough to cover the average cost, are about 9 cents per kWh, as mentioned above. Thus, for the German strategy to be

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[15] Detailed calculations of the back-up power necessary to complement wind and solar energy in Germany can be found in Wagner (2016), who extended the working paper version of this contribution to a greater number of years and somewhat different topics. Wagner and Rachlew (2016) argue that wind and solar energy cannot simply replace nuclear energy as is intended, but need additional gas-power plants to serve as buffers or back-ups. The importance of back-ups, moreover, is emphasized in the meta-study screening German and French publications by Grand et al. (2016). Based on a complex model of the European energy market, Bertsch et al. (2016) predict that, as wind and solar energy is expanded, market forces would automatically provide more gas power plants, even without explicit pricing schemes awarding the flexibility such plants would offer. Hirth (2015) argues that the need to hold back-up power in reserve may limit the optimal wind share to only 20%.

[16] F. Vahrenholt in a Lecture at the Bavarian Academy of Science, January 2012,

[17] Bavaria has practically abandoned its gas power plant Irsching since April 2016, despite the fact that it is one of the newest and most efficient facilities of its kind in Europe, because the prioritized feed-in of green power has reduced its running hours below the profitability threshold. Hirth and Ziegenhagen (2015) report that Germany reduced its back-up power by 15% in the period 2008-2014, while wind and solar power tripled, but they attribute this observation to other reasons, including improvement in forecasting and intra-day trading.

[18] Consumption between 2500 kWh and 5,000 kWh per year. Eurostat, *Database*, Environment and energy, Energy, Energy statistics – prices of natural gas and electricity, Energy statistics – natural gas and electricity prices (from 2007 onwards), Electricity prices for domestic consumers – bi-annual data.

[19] See Fraunhofer ISE (2014), Figure 1; Netztransparenz.de, Erneuerbare Energien Gesetz, EEG-Umlage; and Bundesministerium für Wirtschaft und Energie (2016).

[20] Own calculations based on Dena, German Energy Agency (2016) and Statistik der Kohlenwirtschaft e. V. (2016).

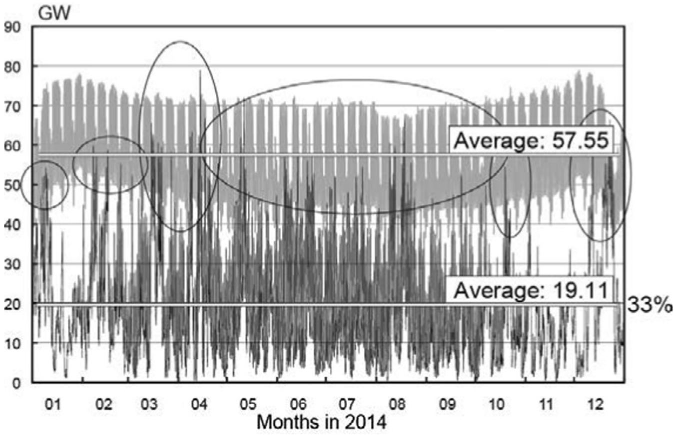

Fig. 7. Doubling German production of wind and solar energy relative to 2014 (hourly data).

economical from a national point of view, the average cost of wind and solar energy would have to fall by over two thirds. Nevertheless, of course, a potential reduction in CO_2 emissions and world-wide learning effects might well justify the extra cost from a global perspective.

To date, black-outs have been avoided, as conventional plants are powerful enough to provide enough electricity in dark and lull periods. Moreover, conventional plants have been kept in place despite the reduction in running hours, as the fixed costs for existing plants were sunk. However, problems may arise when the operating hours for conventional plants are curtailed further in line with the planned expansion of wind and solar power, because it is unclear whether it will be worthwhile to replace worn out old conventional plants with a sufficient number of new ones. Germany has not yet introduced a pricing scheme that would compensate the owners of traditional power plants, including gas-powered plants, for offering their flexibility services. Under the current pricing regime, wind and solar power incur the risk of destroying the business model for conventional plants, even though these plants are indispensable back-ups for green energy.

Moreover, obvious limitations are exposed when the production peaks overshoot consumption, given that conventional plants including hydroelectric power stations can, at best, be driven down to zero output and are unable to absorb and store energy.

As Fig. 4 above suggests, such a point had not been reached until 2014. Despite the huge volatility in production and demand, German power demand exceeded wind and solar power production in each and every hour of 2014.[21] Nevertheless, there were obviously times in March, April and August when the upward production peaks came close to downward demand peaks.

6. Double structure cum storage

This section discusses the efficiency of the double-structure buffering strategy should the production of wind and solar energy be gradually expanded in Germany such that production peaks exceed power consumption. As conventional plants face a non-negativity constraint, the overshooting peaks will either have to be wasted, buffered by stores or absorbed by other countries curtailing their production. This section abstracts from the last possibility and explores the problems involved with a national solution. The subsequent sections deal with the buffering roles of neighbouring countries.

In a first step, it is assumed that Germany buffers as much of the volatility as possible by adjusting the production of conventional plants inversely to wind and solar power and wastes the overshooting production spikes. In a second step it is assumed that the overshooting spikes are stored and released at times of excess demand.

Fig. 7 shows the result of doubling wind and solar power relative to 2014, bringing the share of this energy up to 33% of aggregate output. While 2014 is only one example of the seasonal volatility of demand and supply, it does not seem to be an outlier.[22] As explained above, it is assumed in the calculations that the output of new plants is perfectly correlated with that of existing plants as no new locations can be found.

As shown in the figure, doubling the wind-solar output means that some of the production spikes would overshoot consumption demand. Thus, even if the conventional plants were perfectly flexible, Germany would already have reached the limits of its double-structure buffering strategy, unless the volatility in its energy supply could be buffered by stores or

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[21] In higher resolution data, however, overshooting spikes may have occurred.

[22] Analyses of previous years already conducted by the author did not generate qualitatively different results as the year 2014 was not characterized by unusual weather conditions.

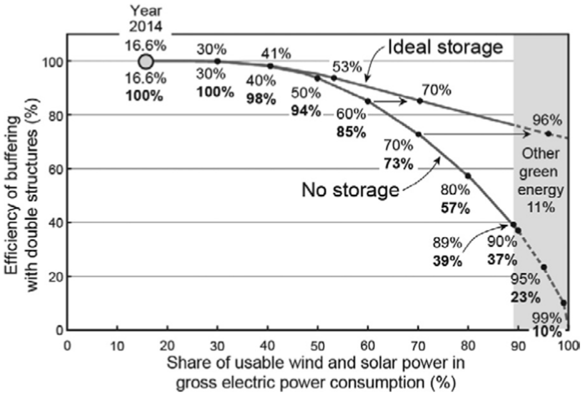

Fig. 8. Efficiency losses from buffering with conventional plants and wasting overshooting production spikes (German hourly data, 2014).
The diagram shows the average efficiency of wind and solar energy resulting from the double-structure strategy as a function of the market share of wind and solar energy in aggregate German power consumption. While the left-hand curve is based on the assumption that the surplus energy resulting from overshooting spikes is wasted, it is assumed for the right-hand curve that the surplus energy is smoothed via perfect stores and supplied to the grid, increasing the share of wind and solar power in total power consumption associated with any given level of double-structure efficiency. The percentages above and directly below the curves give the respective shares of wind and solar energy as a percentage of total power consumption. The bold percentage figures below the left-hand curve give the respective efficiency of the double-structure strategy without storage aid.

other countries or some of the output is wasted.[23] Let us recall that the 33% output share reached by doubling wind and solar power would only generate enough additional energy to enable Germany to decommission all of its remaining nuclear plants. Thus, only higher percentages of wind and solar power would make it possible to crowd out fossil fuel in Germany.

While the volume of the overshooting spikes shown in Fig. 7 is small, only 0.4% of the annual wind and solar production, it would grow progressively with further increases in the production of wind and solar energy, as is shown in Fig. 8. The figure shows two curves that relate the market share of wind and solar energy as measured on the abscissa with the “double-structure efficiency” measured on the ordinate. The left curve is without storage, the right one with ideal, frictionless storage. Double-structure efficiency is defined as the fraction of wind and solar power that does not exceed demand, and hence does not have to be wasted even if no storage device is available.

Consider first the left, downward-bending curve without storage. The curve indicates strongly declining average returns to wind and solar production if Germany only resorts to double-structure buffering. Obviously, efficiency stays close to 100% for wind-solar market shares of up to about 30%, but dwindles progressively towards zero as the market share approaches 100%.[24] Thus, for market shares that go beyond just replacing Germany’s remaining nuclear plants and help reduce CO_2 emissions, energy storage becomes useful, if not indispensable.

It is worth recalling that, as mentioned in Section 1, the share of other green energy sources, i.e. biomass, hydropower and waste, in the power market is 11%. Thus, given the share of these other sources, a wind-solar market share of 89% would be equivalent to a situation where 100% of the electric power stems from renewable sources.[25] This is indicated by the grey area in the diagram.

The downward bending curve shows that a market share of 50% is associated with an efficiency of 94%, a market share of 70% is associated with an efficiency of 73% and a market share of 89% with an average efficiency of just 39%, implying that 61% of the produced wind and solar energy would be lost, if no stores were available.

It is worth noting that the downward-bending curve refers to *average* efficiency of wind and solar production. As the curve is falling, *marginal* efficiency must be even lower than average efficiency. Thus, for example, only 58% of the additional wind-solar energy that would be necessary to increase the market share from 50% to 60% would be usable without storage. Similarly, the step from 60% to 70% involves a marginal efficiency of 39%, the step from 70% to 80% one of 23% and the step from 80% to 89% represents a marginal efficiency of only 10%. Directly at the 89% level, where all electricity stems from renewables, the marginal efficiency is just 6%; i.e. 94% of the last bit of wind-solar energy produced to perfectly crowd out nuclear and fossil fuel and close the gap to the current level of power from hydro dams, waste and biomass will be lost.[26]

Let us now turn to storage, whose potential in the ideal case without storage frictions is represented by the right-hand curve. Storage increases the market share of wind and solar power for any given set of plants and hence for any given level

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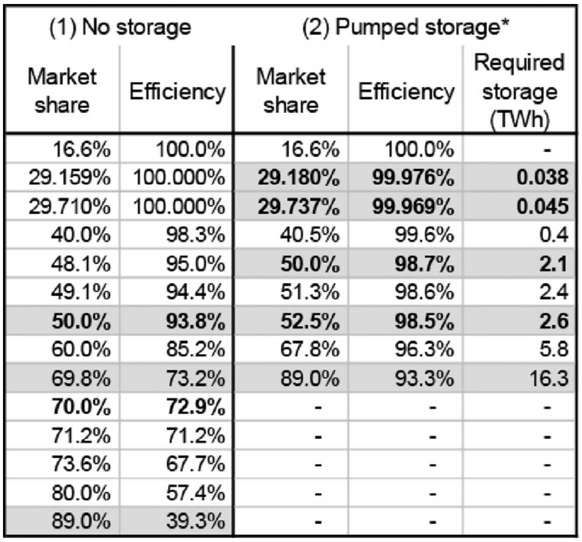
[23] Schill (2014) studies the implications of alternative must-run production levels for conventional plants, showing that the surplus waste is an increasing function of the must-run level.

[24] This confirms the finding of Huber et al. (2014), based on theoretical wind-solar feed-in data derived from a meteorological model, that beyond a wind-solar market share of 30% flexibility requirements increase strongly.

[25] Wagner (2014a) finds that Germanys wasted surplus would be sufficient, if properly smoothed, to service Polish power demand. In another paper Wagner (2014b) argues that Europe’s surplus energy with a 100% renewables share would be enough to service both Poland and Germany.

[26] The step from 90% to 95% would involve a marginal efficiency of 3%, and the step from 95% to 99% one of 7 per mille, but, as explained, this is irrelevant territory in the German case.

Table 1
Efficiency of alternative double-structure-cum-storage strategies (German hourly data, 2014).



(1) No storage		(2) Pumped storage*		
Market share	Efficiency	Market share	Efficiency	Required storage (TWh)
16.6%	100.0%	16.6%	100.0%	-
29.159%	100.000%	**29.180%**	**99.976%**	**0.038**
29.710%	100.000%	**29.737%**	**99.969%**	**0.045**
40.0%	98.3%	40.5%	99.6%	0.4
48.1%	95.0%	**50.0%**	**98.7%**	**2.1**
49.1%	94.4%	51.3%	98.6%	2.4
50.0%	**93.8%**	**52.5%**	**98.5%**	**2.6**
60.0%	85.2%	67.8%	96.3%	5.8
69.8%	73.2%	89.0%	93.3%	16.3
70.0%	**72.9%**	-	-	-
71.2%	71.2%	-	-	-
73.6%	67.7%	-	-	-
80.0%	57.4%	-	-	-
89.0%	39.3%	-	-	-

* Pumped-storage “round-trip” efficiency of 75%, composed of 81% input efficiency (electric power to lake store) and 92.6% output efficiency (lake store to electric power).

of double-structure efficiency measured at the ordinate. It thus shifts the market-share curve to the right. The respective curve shows the case of ideal friction-less storage where all the surplus energy can be used. With ideal storage, a market share of 89% could be reached with plants that, in the case of wasting the surplus, would only have implied a market share of 68%. In the more realistic case of frictions, which is depicted in Table 1, a somewhat higher figure emerges, as will be explained below.

The storage volume required for alternative levels of wind-solar production is shown in Table 1. It is calculated on the assumption that all surplus power is channelled into stores, and subsequently released as quickly as possible by satisfying any excess of demand over wind-solar production (the excess load) when it occurs, displacing the corresponding amount of conventional power. Emptying the stores as quickly as possible at times of insufficient solar and wind is a useful way of gaining free storage space for new overshooting spikes and minimizing the storage space required. As an identical repetition of the consumption and production pattern from year to year is assumed, the storage volume at the beginning of the year is set equal to the volume at the end of the year, while the calculation of minimal storage space again implies that the store is empty for at least one hour per year. As much buffering as possible is done by reducing conventional production – the double structure strategy – and as little as possible by storage.[27] It is assumed that storage involves a round-trip efficiency of 75% (81% input, 92.6% output).

The main column (1) of Table 1 shows the alternative market shares of wind and solar energy and the associated degrees of efficiency of the German double-structure strategy without stores, i.e. basically the information contained in the downward-bending curve of Fig. 8. The main column (2) refers to the case of pumped storage with friction losses. Its subcolumns show the respective (i) wind-solar market share (including the remittances from the stores), (ii) degree of overall efficiency with storage and (iii) required storage volume. Each line in the table shows one particular multiple of the wind and solar devices installed in Germany in 2014.

The first line of the table shows Germany’s status quo in the year 2014 where the wind-solar market share is 16.6% and there are no overshooting spikes. The second and third lines refer to the cases where Germany respectively uses its current 0.038 TWh pumped-storage volume or extends it to 0.045 TWh, which is the maximum the EU’s ESTORAGE project deems feasible.[28] They show, unsurprisingly, that these tiny pumped-storage volumes contribute very little. Even with the extension to 0.045 TWh, Germany could achieve wind-solar market shares of not more than 29.7% without wasting surplus

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[27] This assumption distinguishes the buffering strategy from other assumptions made in the literature. See, for example, Heide et al. (2010, 2011) who, in their forecast model based on European weather data, assume that the store absorbs all variation from overshooting and undershooting spikes alike, while 100% of the power produced and consumed comes from wind and solar energy. In their approach, expanding wind and solar energy further reduces the required storage because the storage need results from filling the wind-solar production deficits with overshooting production, while the overshooting energy production not needed for that purpose is wasted. Huber and Weissbart (2015) have applied this approach to China, assuming more limited contributions by wind and solar power.

[28] See DNV GL (2015), p. 40.

energy. While this is nearly double the volume of 2014, it would not yet mean that all nuclear plants are replaced. So the contribution to mitigating the climate problem would be zero.

The subsequent lines refer to the theoretical cases of higher market shares, which might be reached with or without the help of more pumped-storage plants. Suppose Germany wanted to achieve a wind-solar market share of 50%. Without the help of stores and by wasting the overshooting spikes, it would achieve an efficiency of 93.8%, implying that 6.2% of production would be lost.[29] Alternatively, that same market share could be reached by installing a pumped-storage volume of 2.1 TWh, which increases the overall efficiency to 98.7% and makes it therefore possible to use fewer wind-solar plants. This storage volume is less than one tenth of the 22.1 TWh that in Fig. 5 was shown to be necessary (with ideal stores) in the absence of double-structure buffering.[30] It is still, however, around 55 times Germany's current pumped-storage capacity; or 47 times the volume that would be available after the EU's ESTORAGE program were realized.

Let us now return to the case where a wind-solar market share of 89% is reached that would just fill the gap left after deducting the 11% resulting from hydro power, waste and biomass. As was mentioned above, without storage this market share would result in an efficiency of 39.3%, implying a waste of 60.7% of wind-solar production (last line of column (1)). On the other hand, by installing pumped-stores (with frictions) with a volume of 16.3 TWh – 362 times the volume the ESTORAGE project considers feasible for Germany – it would be possible to boost the efficiency to 93.3% so that the 100% renewables case could be reached with a production level that, without the stores, would merely have resulted in a wind-solar share of 69.8%.

7. Norwegian hydro lakes

If Germany cannot solve its volatility problems in autarchy, other countries may help out by offering buffering services. Currently, there are severe obstacles to this option, as is shown by the frequent occurrence of negative prices for electric energy in Germany and the installation of phase shifter transformers by neighbouring countries that block the international flow of electric power.[31] However, there is significantly more potential in the future once the national grids are better connected and appropriate pricing schemes for offering buffering services are developed.[32] Improving the connections with Norway seems a particularly promising option, as the country has huge hydro dams and also offers many potential locations for further pumped-storage sites.

Hydro plants provide Norway with nearly all of the electric power the country needs, but they may also serve as buffers for German volatility. When the wind in Germany blows and the sun shines, Norway could reduce the outflow from its reservoirs and use German power to service its consumers instead of using its own power. Conversely, in windless, dark periods it could release more water from its hydro lakes to produce excess energy for exports to Germany. Indeed, with a storage capacity of 84 TWh, Norway's hydro dams are huge, theoretically large enough to cover Germany's storage needs even if the country abstains from using its double-structure buffering strategy (see Sections 2 and 3).[33] For example, as was shown in Fig. 5, a trebling of the German wind and solar production, which would bring the wind-solar market share to nearly 50%, would result in a required ideal storage volume of "only" 22.1 TWh.

It is true that despite the huge Norwegian storage volume, there may be the problem that the dams are already full when German wind and solar energy arrives, and that bringing the turbines to a standstill would mean that some of the water flowing in from Norwegian rivers cannot be stored. Thus, in principle, there could be a stock constraint despite the enormous storage volume of the hydro dams. Fortunately, however, Norwegian supply and German demand are positively correlated. As is shown in Figs 5 and 6, Germany would need most of the stored energy from November through March, because this is when the stores empty quickly, but this happens to be when Norwegian dams are rather full, as most of the rain in Norway falls from September to December.[34] Conversely, there would be German excess energy available for filling the dams from April to August. Thus, the problem of insufficient free storage space does not seem to be serious.

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[29] On the basis of meteorologically modeled feed-in data for wind and solar energy in Texas, Denholm and Hand (2011) find that a market share of 50% can be reached at an efficiency of 90%. This is a similar order of magnitude as reported in Table 1. Recall, however, that marginal efficiency for going beyond 50% to 60% would be only 58%.

[30] In the first version of this paper, another storage strategy was used in that the overshooting spikes were stored while the store was reduced by way of withdrawing a steady flow, perhaps for sales in other countries, while the undershooting spikes were buffered with conventional sources. For a market share of 50%, it resulted in a required ideal, friction-less storage volume of 3.5 TWh. See Sinn (2016, July version of this paper).

[31] In 2014 German exports net of imports on average accounted for 6.6% of final German energy consumption. Exports alone stood at 14.5% and imports at 7.9% (see Arbeitsgemeinschaft Energiebilanzen (2016)). Between December 2012 and December 2013, the German energy market had 97 hours with negative spot prices with an average price per kWh of – 4.1 cent as foreign grids struggled to absorb Germany's wind-solar production spikes. Poland and the Czech Republic have installed phase shifter transformers to prevent German energy deliveries to Austria flowing via their grids. Austria, in turn, has resisted improving interconnector capacity with Germany to ward off the transmission of German power, because it wants to force German power companies to buy the power on the Austrian spot market that they have promised in forward contracts, but cannot deliver due to transmission bottlenecks. This has caused political irritations between Austria and Germany, prompting the European regulation agency ACER to propose a separation of the previously joint power markets. Cf. Mihm and Geinitz (2016). Theoretical studies explaining the negative prices include Nicolosi (2011) and Götz, Henkel, Lenck and Lenz (2014).

[32] Cf. Auer and Haas (2016).

[33] Sachverständigenrat für Umweltfragen (2011, p. 157).

[34] See wetter.de, Klima für Norwegen, http://www.wetter.de/klima/europa/norwegen-c47.html.

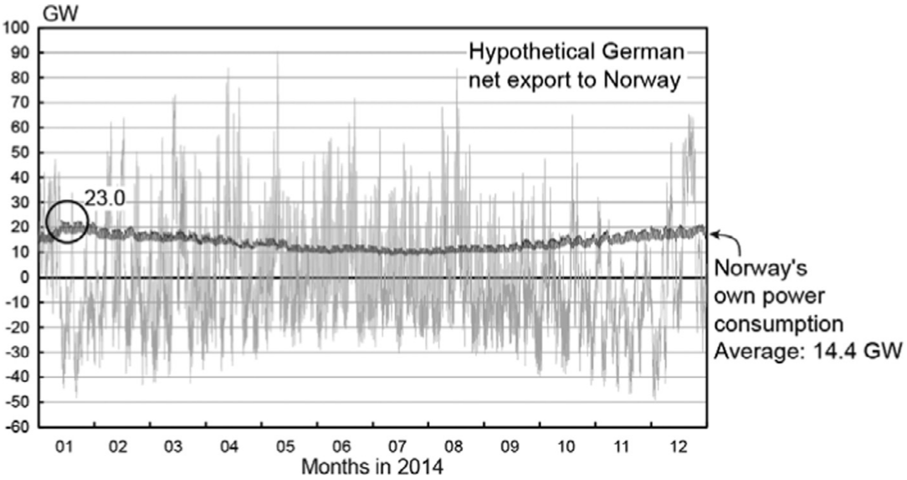

Fig. 9. Norwegian power demand and hypothetical German net export of power to Norway when conventional German plants generate a constant power flow and wind-solar energy has a 53% market share in Germany (hourly data 2014).

Note: This graph shows a hypothetical scenario to demonstrate the role of the power and non-negativity constraints. It is assumed that conventional German plants generate a constant power flow and that the volatility resulting from wind and solar power as well as from German demand would have to be fully buffered by Norway. The more volatile curve shows the hourly net delivery of German power to Norway and the other curve shows Norwegian hourly power demand.

Source: For Germany, see Figure 2. For Norway, European network of transmission system operators for electricity, https://www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month.

There are, however, three other, potentially more problematic constraints related to the“Norwegian solution” that also need to be taken into account:

(1) *The transmission constraint*
The capacity of deep-sea cables between Germany and Norway might be insufficient.

(2) *The power constraint*
The country's power turbines might not have enough power in dark, windless periods when both Norwegian consumption and the re-export of power to Germany need to be serviced.

(3) *The non-negativity constraint*
As hydro plants cannot go in reverse mode, pumping lake water upstream, Norway would have to absorb the German power by stopping the turbines, servicing its own consumption with the import from Germany and accumulating the river energy not needed in the dams. However, Norway's own consumption may be too small to absorb all the power coming in.

To help assess the importance of these constraints, Fig. 9 shows the Norwegian power demand as well as the net delivery of power from Germany that would be necessary to absorb the volatility resulting from a 53% wind and solar market share in Germany, assuming that Germany gives up its double-structure strategy and has its conventional plants run at constant speed. This is the case where in autarchy double structure buffering and wasting the overshooting spikes would generate a wind-solar market share of 50%. (See Fig. 8 and Table 1.) The purpose of this figure is not yet to discuss a viable solution but to demonstrate the challenges and roles of the three constraints in a thought experiment where the two markets, and only these markets, are combined to a common “copper plate”. The case of a broader market incorporating more countries will be considered in the following section. As in Fig. 5, the German volatility results from proportionally scaling up the country's 2014 hourly wind and solar power production, while the hourly demand pattern stays unchanged. The (positive and negative) net delivery to Norway is the algebraic difference between German demand and German wind-solar supply. While Norway imports the energy from Germany and re-exports it as needed, it is assumed that its average annual power generation remains constant.

Let us first consider the transmission constraint (1). As the graph shows, the power spikes that would have to be transmitted through the deep-sea cables to Norway often lie in the range of about 80 GW and peak at about 90 GW, while the retransmission from Norway to Germany would be a bit smoother, peaking at around 50 GW. These are huge numbers relative to the transmission capacity currently available. In 2011 the transmission capacity was 1.5 GW, while an expansion to 4.3 GW was planned.[35] In September 2016 the construction works for the NordLink cable with a capacity of 1.4 GW started, which is scheduled to become available in 2020.[36] Thus the transmission capacity would have to be increased by a factor of about 60 relative to today and 20 relative to what has been planned.

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[35] See Sachverständigenrat für Umweltfragen (2011).

[36] See http://www.ndr.de/nachrichten/schleswig-holstein/Spatenstich-fuer-XXL-Stromtrasse-nach-Norwegen, nordlink130.html.

Consider next the power constraint (2). The graph shows that Norwegian demand peaks in mid-January at 23.0 GW. This is below, but close to the nominal production capacity of Norwegian plants, which stands at 29 GW.[37] Obviously, this capacity would be insufficient to produce enough energy to service both Norwegian demand and the return delivery of energy to Germany in dark and windless periods. The curve depicting German net delivery to Norway has negative peaks of nearly −50 GW from November to January, while Norwegian demand often peaks close to the 23 GW mentioned above in similar periods of the year. Thus, the capacity of Norway's turbines would have to increase by over 2½ fold to accommodate the needs.

Let us finally turn to the non-negativity constraint (3). Fig. 9 shows that imports from Germany would have huge spikes of up to 90 GW (early May), overshooting Norwegian consumption more than sevenfold, by up to 78 GW. These overshooting spikes cannot be stored by simply stopping Norway's own production, as the hydro plants cannot be used to pump water upstream.

This is obviously a very serious constraint, because Norway has hardly any pumped-storage plants. The few devices that do exist are not used for energy storage, but to prevent upper lakes from drying out in periods with too little rain and tilting ecologically.[38]

Solving the problem by investing in new plants is not easy, as geological conditions often do not allow for the complementation of an existing hydro lake with a second downstream lake from which the water could be pumped back upstream. It is true that hydro power lakes sometimes empty into fjords, which could then serve as the "second lake" from which water can be pumped back. Fjord water could also be pumped uphill into artificial basins yet to be built. However, such strategies involve high ecological risks and are therefore not seen as viable options in Europe.[39] Nevertheless, Norway does offer significant pumped-storage potentials.

Currently, the pumped-storages plants of Western Europe including Switzerland and Norway have at most 327 GWh of storage volume.[40] According to the ESTORAGE project, which looked for economic solutions by combining existing lakes with pipes and flexible pumped-storage turbines, another 2.291 TWh of pumped-storage volume could reasonably be built to achieve a total storage volume of up to 2.618 TWh in Western Europe.[41] The expansion would constitute an eightfold increase in the current pumped-storage volume available in Western Europe. Of this increase, 59% or 1.356 TWh could be built in Norway alone.[42] It would be equivalent to 1259 plants of the current German variety, although much bigger plants are planned in Norway.

This is a sizeable number, but it would nevertheless be small compared to the number of plants that would be required if hydro lakes and pumped-storage lakes were to buffer Germany's volatility without resorting to the double structure strategy. To buffer the overshooting spikes shown in Fig. 9, which would result from a 53% wind and solar market share in Germany and remain after maximal hydro-dam buffering in Norway, and to allow Germany's conventional plants to produce a constant flow of output, an ideal pumped-storage capacity of 8.2 TWh would be needed in the scenario without frictions, and 6.64 TWh in the realistic case with frictions. This is much less than the German pumped-storage requirements mentioned in Fig. 5, because the Norwegian hydro dams would absorb most of the volatility. Nevertheless, it would still be nearly five times the maximum considered feasible in Norway and Germany together (1.401 TWh) by the ESTORAGE project.[43]

8. Double structures, hydro dams and extended copper plates

In view of the limited potential of a pure hydro-dam buffering strategy, this section investigates a more balanced strategy that combines hydro-dam buffering with ordinary double-structure buffering of the German kind, while exploiting potential diversification gains for power demand, as well as for wind and solar output, by combining alternative countries in a common "copper plate".[44] Firstly, a common market including Germany and Norway is modelled; and subsequently, in a second step, Switzerland, Austria and Denmark, three neighbouring countries with significant shares of green production facilities, are added to the copper plate. The trade links of the five countries are thereby fully taken into account.

The calculations aim to assess the pumped-storage volume needed for alternative wind-solar market shares in Germany and in the respective combined market, if energy wastes are to be avoided. They are slightly too optimistic, as not all data on

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[37] See International Hydropower Association, 2015 Key Trends in Hydropower, p. 2, https://www.hydropower.org/sites/default/files/publications-docs/IHA%202015%20Key%20Trends%20in%20Hydropower.pdf.

[38] In 2014 Norway's pumped stores generated an accumulated annual gross flow of 780 GWh. This is a tiny number, which should not be confused with information about the storage volume even though it is expressed in terms of GWh. 780 GWh is 12% of Germany's 5,857 GWh which were produced from a storage volume of just 38 GWh. See Eurostat, Database Environment and Energy, Energy, Energy statistics – quantities, annual data, Energy statistics – Supply, transformation and consumption, Supply, transformation and consumption of electricity – annual data.

[39] There is, however, a sea-water pumped-storage plant in Okinawa, Japan. See Hiratsuka, Arai and Yoshimura (1993).

[40] See European Commission (2016).

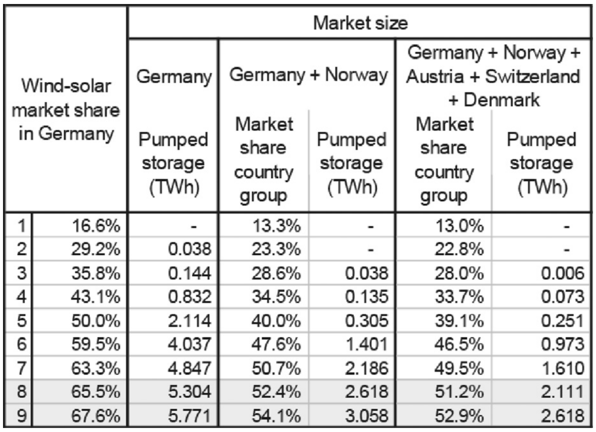
[41] See DNV GL (2015), p. 10, and European Commission (2016).

[42] DNV GL (2015), p. 40 and p. 43. The study shows that five percentage points or 114 GWh of the feasible storage volume would be located in very distant regions in northern Norway.

[43] This is the sum of the existing German volume of 0.038 TWh and the new volume of 1.356 TWh for Norway and 0.007 TWh for Germany that the ESTORAGE project considers feasible. See DNV GL (2015), p. 40.

[44] For studies concentrating on the design of European and national power lines and grid extensions to buffer the volatility see, for example, Spiecker and Weber (2012), Weigt et al. (2010), Neuhoff et al. (2013), Hagspiel et al. (2014) and Hirth and Ziegenhagen (2015). For a study focusing on the USA, see Heal (2016).

Table 2
Pumped-storage needs and wind-solar market shares with double-structure and hydro-dam buffering for alternative country groups (hourly data, 2014).



Wind-solar market share in Germany		Market size: Germany	Germany + Norway		Germany + Norway + Austria + Switzerland + Denmark	
		Pumped storage (TWh)	Market share country group	Pumped storage (TWh)	Market share country group	Pumped storage (TWh)
1	16.6%	-	13.3%	-	13.0%	-
2	29.2%	0.038	23.3%	-	22.8%	-
3	35.8%	0.144	28.6%	0.038	28.0%	0.006
4	43.1%	0.832	34.5%	0.135	33.7%	0.073
5	50.0%	2.114	40.0%	0.305	39.1%	0.251
6	59.5%	4.037	47.6%	1.401	46.5%	0.973
7	63.3%	4.847	50.7%	2.186	49.5%	1.610
8	65.5%	5.304	52.4%	2.618	51.2%	2.111
9	67.6%	5.771	54.1%	3.058	52.9%	2.618

volatile energy sources are available. While hourly data on power demand have been published for all five countries, hourly data for wind power are only available for Germany, Denmark and Austria, and for solar power in the cases of Germany and Denmark.[45] It seems, however, that the data not published on an hourly basis refer to negligible quantities.[46]

It is assumed that as much of the volatility stemming from wind and solar energy as possible is buffered by both conventional plants and hydro dams both facing non-negativity constraints; and that pumped-storage plants are only used for buffering the production spikes, if any, that overshoot combined international demand. The method used for calculating the minimal storage volume is the same as in Section 6. While pumped storage involves the same frictions as assumed above (see Footnote, Table 1), hydro-dam buffering is frictionless, given that no round-trip water flows occur. It is assumed that hydro-dam buffering is mean preserving, while conventional power production is crowded out, as the production of wind and solar energy is expanded.

The expansion towards higher wind-solar market shares again assumes that the relative distribution of plants across the locations (within the countries and across the countries) remains unchanged such that the new plants are perfectly correlated with the existing ones. Thus the relative wind-solar production quantities across the countries remain the same as before the expansion. The pumped-storage plants are assumed to be commonly used, and the remittances from these plants (after deducting the friction losses) to the respective countries are proportional to their wind and solar production figures. Potential international diversification gains from non-perfectly correlated regional demand and wind-solar supply patterns are automatically taken into account by aggregating the markets. The transmission (1) and power (2) constraints, as well as the stock constraint that might result from already filled hydro reservoirs, are assumed not to be binding.

Table 2 presents an informative selection from a large number of calculations that were made for (i) alternative wind-solar market shares in Germany, (ii) the corresponding wind-solar shares in the respective aggregate international market and (iii) the pumped-storage volumes required in the group of countries considered. The second column of Table 2 shows alternative wind-solar market shares in Germany, while the third, repeating parts of Table 1, states the required pumped-storage volume if Germany operates in autarchy. The fourth and fifth columns give the wind-solar market share in the joint German–Norwegian market and the required pumped-storage volume in Germany and Norway that would result from the same installations of wind and solar plants. The sixth and seventh columns provide the analogous results for the extended market of all five countries. The calculations use the 2014 hourly demand data, as well as the available hourly data on wind and solar power production for the respective country groups, as explained above. The first column numbers the lines and, as a point of reference, the first line shows the status quo of the year 2014 where no storage was needed as there were no overshooting spikes.

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[45] The data are taken from: Amprion, http://www.amprion.net/windenergieeinspeisung, and http://www.amprion.net/photovoltaikeinspeisung; Tennet, http://www.tennettso.de/site/Transparenz/veroeffentlichungen/netzkennzahlen/tatsaechliche-und-prognostizierte-windenergieeinspeisung, and http://www.tennettso.de/site/Transparenz/veroeffentlichungen/netzkennzahlen/tatsaechliche-und-prognostizierte-solarenergieeinspeisung_land?lang=de_DE; Transnet BW, https://www.transnetbw.de/de/transparenz/ marktdaten/kennzahlen; 50 Hertz, http://www.50hertz.com/de/Kennzahlen/Windenergie/Hochrechnung, and http://www.50hertz.com/de/Kennzahlen/Photovoltaik/Hochrechnung; Austrian Power Grid, https://www.apg.at/de/markt/Markttransparenz/erzeugung/Erzeugung%20pro%20Typ; Energinet DK, http://www.energinet.dk/en/el/engrosmarked/udtraek-af-markedsdata/Sider/default.aspx; European Network of Transmission System Operators for Electricity, https://www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month.

[46] E.g. wind power is only 1.6% of power production in Norway and 0.2% in Switzerland, and solar power accounts for 0.0% in Norway and Switzerland. See European Network of Transmission System Operators for Electricity, Detailed Monthly Production, https://www.entsoe.eu/db-query/production/monthly-production-for-a-specific-country.

Let us first consider the case where Germany and Norway merge, focusing on lines 2 and 3. If no further pumped-storage plants are built and the German storage volume remains at its present level of 0.038 TWh, Norwegian hydro-dam buffering would increase the maximal market share of wind and solar energy that Germany could realize without wasting some of its energy from 29.2% (line 2) to 35.8% (line 3). The latter would be equivalent to a wind-solar share of 28.6% (line 3) in the joint German–Norwegian market.

Even higher market shares are possible when Switzerland, Austria and Denmark join the German–Norwegian market. Denmark has no stores, but adds volatility due to its heavy reliance on wind power, which has a market share of 42.7%.[47] On the other hand, mountainous Switzerland and Austria have a number of pumped-storage plants that may help to buffer the volatility. While no data on the Swiss and Austrian storage volumes have been published, an estimate based on published production data would put this volume at 0.035 TWh.[48] This is similar to Germany's 0.038 TWh existing storage volume, bringing the total existing storage volume of the five countries considered to 0.073 TWh. As line 4 shows, the German wind-solar market share could now be increased to 43.1%, while the maximal wind-solar share in the aggregate market of all five countries considered would be equal to 33.7%.

Let us now discuss the necessary expansions of the pumped-storage volume to achieve specific wind-solar market shares and compare them with the geologically feasible expansion data according to the ESTORAGE project. Line 5 shows that to reach a market share of 50% in autarchy, Germany would need a (domestic or foreign) pumped-storage volume of 2.114 TWh, which is equivalent to 1962 pumped-storage plants of the German type. However, if supported by Norway's hydro dams, it would only need a pumped-storage volume of 0.305 TWh, equivalent to 283 German plants. This is a huge reduction in the required pumped-storage volume to only one seventh, confirming the hope that the creation of a German–Norwegian copper plate would substantially alleviate the German volatility problem.[49] Building the additional 267 GWh of pumped-storage volume (in addition to the 0.038 TWh Germany currently has) to reach the required volume is not an impossible task, as it would amount to only about one fifth of the 1.363 TWh additional pumped-storage volume that the ESTORAGE project considers feasible for Norway and Germany.

To achieve a wind-solar market share of 50% for Germany while integrating all five countries, an overall pumped-storage volume of 0.251 TWh is needed. Interestingly enough, this volume is only slightly smaller than the 0.305 TWh that would be required if only Germany and Norway were combined. Thus, the additional hydro-dam and double-structure buffering possibilities, as well as the potential diversification gains that Austria, Switzerland and Denmark bring in, largely outweigh the need to handle the volatility of Denmark's wind power. As the table shows, a 50% wind-solar market share for Germany is equivalent to a market share of 39.1% in the five countries taken together.

As seen in line 6, more wind and solar power would be possible in Germany, if Norway and Germany chose to maximally expand their pumped-storage volumes according to the ESTORAGE project, bringing the total volume of these two countries to the 1.401 TWh mentioned towards the end of Section 9.[50] In this case, a maximal German wind-solar market share of 59.5% would be possible if no spikes are to be wasted, corresponding to a wind-solar market share of 47.6% in the combined Norwegian-German market. As Germany has a market share of 11% for other renewables (biomass, waste, hydro dams) and Norway one of 100% (hydro dams), the non-wind-solar renewables in the joint Norwegian-German market would produce 29% of aggregate demand, bringing the total share of renewables in the joint market to about 77%.

Interestingly enough, despite their huge storage potential of 84 TWh, a comparison of lines 2, 3 and 6 shows that Norwegian hydro dams turn out to be less important for Germany's needs than the potential additional pumped stores, nearly all of which would be located in Norway. While the pumped stores make it possible to increase the German wind-solar market share by 23.7 percentage points (from 35.8% to 59.5%), the hydro dams, taken by themselves, would only allow an expansion of 6.6 percentage points (from 29.2% to 35.8%). This shows the importance of the non-negativity constraint discussed in the previous section. Thus, the value of the Norwegian strategy for Germany lies more in the grid expansion as such than in the Norwegian 84 TWh hydro-storage volume. Had there been no hydro stores, and had Norway's own power demand been serviced with conventional fossil fuel plants supported by the pumped stores, the potential buffering service for Germany would have been largely the same; although, of course, the service would have come from an environmentally problematic energy source.

Even in Austria, Germany and Switzerland more pumped stores could be built according to the ESTORAGE project. Adding the ESTORAGE estimate for the potential expansion by 0.166 TWh in Switzerland and by 0.008 TWh in Austria, as well as the above estimate of these countries' existing pumped-storage volume of 0.035 TWh to the German–Norwegian maximum

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[47] See European Network of Transmission System Operators for Electricity, Detailed Monthly Production, https://www.entsoe.eu/db-query/production/monthly-production-for-a-specific-country. In 2014, wind and solar power together accounted for 44.7% in Denmark.

[48] According to Eurostat data, in 2014 Austrian and German pumped-storage plants produced accumulated gross energy flows of 3,826 GWh and 5,857 GWh, respectively (see Eurostat, Database Environment and Energy, Energy, Energy statistics – quantities, annual data, Energy statistics – Supply, transformation and consumption, Supply, transformation and consumption of electricity – annual data). Similarly, Swiss statistics show that Switzerland produced 1,585 GWh (see Swiss Federal Office of Energy, Topics, Hydropower, http://www.bfe.admin.ch/themen/00490/00491/index.html?lang=en). Assuming that Swiss and Austrian plants on average have the same ratios of production flows and storage volumes as Germany, which has a joint storage volume of 0.038 TWh, a storage volume of 24,627 MWh for Austria and 10,202 MWh for Switzerland can be estimated.

[49] This fits to a result of a pricing study carried out by Hirth (2016). Using Swedish data, the author shows that the value of wind power declines with an increasing market share, but less so the more hydro power is available.

[50] See also DNV GL (2015), p. 40.

of 1.401 TWh, gives a future maximal pumped-storage volume of 1.610 TWh for all five countries taken together.[51] As line 7 shows, with this pumped-storage volume, Germany's wind-solar market share could be expanded to 63.3%, and the corresponding wind-solar share in the aggregate market of the five countries would be 49.5%.

Thus, even when all pumped-storage plants are built that the ESTORAGE project deems feasible and when double-structure buffering and hydro-dam buffering are used to their fullest extent, no more than half of the energy in the expanded copper plate including Norway, Denmark, Germany, Austria and Switzerland could be produced with wind and solar power without wasting some of this power.

As seen in lines 8 and 9, which are marked in grey, wind-solar market shares above 50% would require more pumped-storage volume than could be built in the countries considered. For example, a wind-solar market share of 52.4% in the combined German–Norwegian market would only be possible if these two countries could exclusively use the entire 2.618 TWh that could be made available in *all* western European countries according to the ESTORAGE study (line 8). Similarly, a share of 52.9% could be reached in the joint market of all five countries if all potential future storage plants of western Europe could be used by these five countries alone (line 9).

9. Further options

Whether these results suggest that the glass is half full or half empty depends on how one looks at the matter. Optimists would emphasize the substantial crowding out of fossil fuel, though not fossil fuel plants, that they imply. Pessimists might recall that, according to Fig. 1, electric power accounts for only one fifth of the total energy consumption and that fossil fuel use outside the electricity sector constitutes 71% of Germany's entire final energy consumption. In view of the difficulties involved in trying to push the wind-solar market share in power production beyond 50%, how can Germany then hope to bite significantly into this 71% by way of expanding the use of electricity, for example by moving to electric cars? After all, expanding electricity production would not imply that pumped storage volumes could also be expanded.

Some have argued that the emergence of electric cars would make it possible to use their lithium-ion batteries as buffers. However, these batteries are very expensive and cannot be used for seasonal storage, given that the cars have to be available for daily use.[52] Car batteries would be useful to smooth intra-day volatility while the cars are parked, but as argued above in the context of Fig. 5, such high frequency volatility is not the issue.

However, there are other storage options.[53] Arguably, the most promising alternative to pumped storage is methane storage.[54] Methane is basically the same as natural gas. Germany has a dense methane distribution net and a methane storage capacity of 267 TWh, which is far more than would be needed to smooth the normal volatility in German power demand and supply.[55] The problem, however, lies in converting electric power to methane and back. The available technologies are inefficient and expensive.[56] Firstly, traditional alkaline electrolysis requires a continuous input of electric power and cannot easily handle volatile inputs. Other short-term stores are needed before electrolysis can begin. Secondly, methanation requires substantial supplies of CO_2, which may be an unwanted by-product of production processes but cannot cheaply be delivered in a suitable form. In combination with carbon capture and storage strategies, however, such supply might become more cheaply available. Thirdly, the methanation process implies substantial production of waste heat in the summer, when the green energy surplus that is to be stored is produced. Estimates of the original electric energy input that can be recuperated by using methane to run a gas power plant typically range from a fifth to a third.[57] Thus, even without counting the cost of the appliances involved – namely the methanation devices, the gas power plants and the storages – the electric power coming out of the gas power stations would cost three to five times as much as the original electric power input. Taking the cost of the appliances into account, the production cost would multiply.

Of course, the methane could be used for heating rather than electricity production. While this would improve technical efficiency, it would mean converting a high quality energy resource (electric current) into a low quality resource (heat), which would come close to wasting the electric power. According to Carnot's Theorem, any conversion of heat into motion

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[51] Ibidem.

[52] The battery of the most powerful variant of the Tesla cars stores about 90 kWh, while the BMW i3, popular in Germany, stores only about 19 kWh. One million of Tesla's most powerful batteries would be equivalent to about 80 pumped-storage plants of the German kind.

[53] See Rosen (2007), Sterner (2009), Fuchs et al. (2012), Vahrenholt (2012) and Lund et al. (2015) for overviews of the available options.

[54] For a discussion of alternative chemical storage options see Sterner (2009) and Nitsch et al. (2010, Section 4.1.2 , p. 74–79).

[55] See Bundesministerium für Wirtschaft und Energie (2015). The ministry states a storage volume of 24.6 billion m^3. The figure mentioned in the text that follows as $1m^3$ is equivalent to 10.848 kWh.

[56] Firstly, hydrogen H_2 is produced from water (H_2O) by electrolysis, i.e. by using the electric power to split off the oxygen (O_2). In a second step the hydrogen is combined with carbon dioxide (CO_2) by a chemical process that normally requires high temperature and pressure, generating methane (CH_4) and water.

[57] Sometimes even bigger variations are reported. For example, Jentsch (2015, p. 10 n) reports a degree of efficiency for electrolysis of between 40–67% (current) and 62–79% (future). Götz, Lefebvre et al. (2016, p. 1383) report an efficiency degree of 70% (current). While the maximum theoretical degree of efficiency for producing methane from hydrogen is 83 %, the latter authors report 78% for the efficiency actually achieved. The degree of efficiency for the most modern combined gas and steam turbines reaches 60%. This gives an overall efficiency degree ranging between 19% and 37%. The German government optimistically reports an overall efficiency degree of 35% on its web page: https://www.bundesregierung.de/Content/DE/Artikel/2014/12/2014-12-16-nicht-abschalten-sondern-umwandeln.html.

energy or electric energy involves huge efficiency losses for physical reasons, quite apart from the technical reasons that add to these losses.[58]

The methane generated from electricity costs a multiple of the methane (natural gas) available in the market. While a kilowatt hour of methane from Russia in the first quarter of 2016 cost a power station 2.42 cents, the same amount of methane produced from wind and solar power would cost about 25 cents, i.e. about 10 times as much.[59]

Instead of methane, hydrogen could be stored. This would theoretically reduce the inefficiency insofar as the loss from converting hydrogen to methane could be avoided. However, in practice, round trip efficiency of hydrogen storage is hardly much higher than methane storage.[60] Moreover, hydrogen cannot be stored as easily as methane given that it diffuses through all kinds of pipeline materials and tends to corrode them.

Given the difficulties with seasonal storage solutions, it has been argued that it might eventually be better to waste the overshooting spikes, rather than storing them and installing correspondingly more wind-solar plants to compensate for the losses.[61] Indeed, German power grid companies are regularly paying wind turbine owners to not produce electricity to avoid unusable surplus production or even negative prices. However, this results from the legal priority right they enjoy and says very little about its economic rationality.[62] In view of the strongly diminishing marginal returns of wind-solar production (Fig. 8) with a marginal wind-solar efficiency of just 6% when wind, solar, biomass, waste and hydro power account for all of Germany's energy needs, this view does not seem overly convincing. While the wasting strategy could be considered for low values of the wind-solar market share, solutions with storage seem unavoidable for sizeable market shares.

Whether or not wasting is cheaper than storage is an open question. While the authors of the ESTORAGE study made economic viability an explicit selection criterion, the study lacks a detailed analysis of the economic benefits and costs involved. Unfortunately, a reliable analysis cannot be provided here either, as the cost per unit of storage volume of Norwegian pumped-storage solutions is not available to the author.

Nevertheless, a back-of-the-envelope calculation of the revenue from storage in terms of saved wind-solar plants is at least possible. Let us consider again line 7 of Table 2, which refers to the maximal wind-solar market share of 49.5% that could be reached in the five countries when all pumped-storage plants (1.610 TWh) were constructed that the ESTORAGE project deems feasible. This market share corresponds to a wind-solar production gross of pumped-storage friction losses equal to 49.9% of aggregate demand. To reach the market share of 49.5% despite wasting the overshooting spikes, a wind-solar production equal to 51.5% of aggregate demand would be necessary. The necessary increase in gross output of 1.6 percentage points difference, which is equivalent to a an extra production of 1.396 GW or 12,225 GWh in one year, is the waste saved due to the pumped-storage plants, which have the above-mentioned volume of 1.610 TWh.

Let us assume an average wind-solar cost of €0.09 per kWh or €90,000 per GWh. It follows that the economic value of the overshooting spikes that in one year could be saved is about €1.100 billion or €683,519 per GWh storage volume. Discounted at a rate of 2%, this corresponds to an *average* revenue per GWh storage volume in terms of the present value of saved energy of € 34.86 million, or a present value of € 56.11 billion for the entire pumped storage volume that could be installed.

By similar reasoning, the *marginal* revenue in terms of the present value of spared wind-solar production of one additional GWh storage volume can be calculated provided that 1.610 TWh storage volume are already installed. One additional GWh storage would make it possible to generate an extra production of wind-solar power of 3.12 MW or 27.3 GWh in one year, which corresponds to a present value of €125.36 million per GWh.

Whether this is enough to justify the investment depends on the cost of pumped-storage plants. German costs are known, but the plants are tiny and expensive. German plants have an average volume of 1.077 GWh, typically involve the construction of a new water basin, and cost between €350 million and €600 million.[63] It therefore would not be worthwhile to build them for seasonal storage purposes. By contrast, the new plants the ESTORAGE project considers for Norway have an average volume of 42 GWh,[64] and they only involve connecting existing lakes, as this was one of the selection criteria. Given that the construction and service cost of a pumped-storage plant that just connects existing lakes depends on the flow capacity of the power station, rather than the volumes of the lakes, it seems that the Norwegian costs might only be a

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[58] Thus, for example, a plant that uses vapor at a temperature of 800°C and exhausts it at 100°Ccannot have an efficiency degree of more than 65.2%. In practice, gas power stations recoup only about half the energy contained in methane into electric energy.

[59] See Götz, Lefebvre et al. (2016), Table 9, which offers an overview of several studies on the production cost of substitute natural gas produced. Cf. also Statistik der Kohlenwirtschaft e. V. (2016).

[60] According to Klaus et al. (2010, p. 38), the round-trip efficiency would be 7 percentage points higher than that of methane storage, which the authors estimate at 35%. In a UK pilot plant storing wind and solar power as hydrogen and converting the hydrogen back to electric power by way of using a micro-hydroelectric turbine, a round-trip efficiency of just 16% was achieved. See Gammon et al. (2006).

[61] See Schill (2014).

[62] The payments for stopping the turbines are 90% of the administered feed-in tariffs that could have been earned. The compensation payments have been rising progressively in recent years. In 2015, German producers of wind power were entitled to 366 million euros in compensation payments. See Bundesnetzagentur (2016).

[63] See "Energiespeicher Riedl: 2016 wird über Millionen-Bau entschieden", *Passauer Neue Presse* online, http://www.pnp.de/lokales/stadt_und_landkreis_passau/hauzenberg/1306395_Ein-Kraftpaket-in-Wartestellung.html, and "Jochberg: Viele Fragen offen", *Süddeutsche Zeitung* online, http://www.sueddeutsche.de/muenchen/wolfratshausen/geplantes-pumpspeicherwerk-jochberg-viele-fragen-offen-1.1610717.

[64] See DNV GL (2015), p. 72 and own calculations.

small fraction of the respective German costs, perhaps even 1/40 or so, which may justify them being erected to avoid the waste. However, future research will have to provide a thorough answer to this question.

An entirely different alternative to producing electricity from weather-dependent sources would be to make the existing fossil fuel plants "clean" by capturing their CO_2 emissions and storing it. This would allow them to operate for another couple of decades. The available options are now well-researched.[65] The main problem with such a solution is the space that it requires. When fossil fuels are burned, each carbon atom is combined with two oxygen atoms, and these must also be disposed of. This implies that the waste volume is much bigger than the space emptied by extracting the resources. Burning a cubic meter of high-grade anthracite coal, for instance, results in 5.4 cubic meters of liquid CO_2.[66] Another problem is the huge energy cost of absorbing liquid CO_2 from the exhaust pipes of fossil fuel plants. As this involves multiple heating and cooling substances that would carry the CO_2, about one third of the generated energy is lost. A third problem is safety considerations due to the fact that the higher weight of CO_2 relative to oxygen makes deposit leakages potentially dangerous when the air is still.[67] This is one of the reasons why it has proven impossible to install a CCS plant in Germany to date.

For the time being, Germany might also consider reducing its CO_2 emissions by replacing coal with gas power plants. Methane is amply available and, as half of its energy comes from the combustion of hydrogen rather than carbon atoms, its combustion generates only about half of the CO_2 emissions that coal-fired plants do. Moreover, methane would make it easily possible to reduce the output of climate gases in traffic, as the frequent conversions of gasoline engines to methane consumption in Italy and elsewhere are showing.

Finally, Germany and other countries might reconsider the nuclear option. Nuclear fusion, which allows a safe operation as fusion reactors cannot melt down and emit only negligible amounts of radioactivity, might be the most promising option for the long run. Indeed, the international ITER consortium in Geneva as well as Germany's Stellerator project in Greifswald have made significant progress in recent years.

For the time being, however, safer fission reactors could be considered. Sweden, Germany's long-term role model for social reforms, has cancelled its pioneering decision of 1980 (after the Harrisburg accident) to exit nuclear power by 2010, and is now planning to construct ten new reactors as replacements for older ones.[68] When a new generation of policy makers takes office, the nuclear exit decision may well be re-considered by the German electorate.

10. Top ten takeaways

Scaling the volatile 2014 hourly wind-solar power output of Germany and a number of neighbouring countries, this paper explores the buffering possibilities resulting from grid expansions, back-up plants, demand management, Norwegian hydro dams, and, in particular, pumped-stores using the results of the EU's ESTORAGE project. These are the paper's top ten takeaways:

(1) Smoothing German wind and solar power jointly requires less storage space than smoothing either of them separately, as wind and solar energy exhibit a negative seasonal correlation.

(2) Smoothing both German power demand and wind-solar power supply at the 2014 market share (16.6%) would require an ideal friction-less storage volume of 11.3 TWh. While this is about the same as is needed to smooth the wind-solar supply alone, storage requirements will increase sharply as wind-solar production expands. At a market share of 50%, the required storage volume would be 22.1 TWh, equivalent to 20,517 plants of the average German size. This is 491 times the amount that the ESTORAGE project deems feasible for Germany.

(3) Ideal demand management, which would perfectly correlate demand and wind-solar energy supply, would reduce the storage volume needed to smooth Germany's current excess of demand over wind-solar supply by no more than 0.9%, 5.9% or 11.0%, respectively, depending on whether demand is adjusted during a day, a week or a month.

(4) In view of the storage problems, Germany has opted for double-structure buffering with conventional plants serving as back-ups. Double-structure buffering involves double fixed costs. From a national point of view, without taking ecological considerations into account, the installation of new wind and solar plants pays off if, and only if, their *average* cost is below the *marginal* cost of producing electricity from fossil fuels. Today, the wind-solar plants are a long way from satisfying this condition.

(5) If Germany were to rely solely on domestic double-structure buffering, it would have to waste the overshooting production spikes from wind and solar production. The marginal and average wind-solar efficiency would decline progressively beyond a market share of 30%, i.e. in the range where a contribution to mitigating the climate change can be made, because nuclear power has been fully replaced by wind-solar power. If the country nonetheless wanted to also crowd out its entire power production from fossil fuels, the average waste would be 61% and the marginal waste 94% of its gross wind-solar production, given the current level of other renewables (waste, biomass and hydro).

(6) If Germany tried to achieve a 50% wind-solar market share without wasting the surplus energy by combining double-structure buffering and pumped-storage, it would need a pumped-storage volume of 2.1 TWh. This is less than a tenth

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[65] Cf. IEA (2016), Scott et al. (2013), Koelbl et al. (2014) and Sinn (2012, pp. 53–60).

[66] See Sinn (2012, p. 56, Table 2.1).

[67] See Ploetz (2003).

[68] See Milne (2016).

of what it would need without double-structure buffering, but nevertheless 47 times the maximum the ESTORAGE project deems feasible for Germany.

(7) It might help Germany to be able to use Norway's 84 TWh of hydro dams as buffers by connecting the grids and creating a common electricity market. However, hydro-dam buffering suffers from a non-negativity constraint just as conventional plants. If Germany tried to unload the volatility resulting from a 53% wind-solar market share onto Norway without using domestic back-ups, its production spikes would overshoot the Norwegian hydro-dam absorption possibilities more than sevenfold. To smooth the remaining volatility, both countries would need a combined pumped-storage volume of 6.64 TWh, which is nearly five times the maximum deemed feasible by the ESTORAGE project (1.401 TWh).

(8) Norwegian hydro-dam buffering would nevertheless be useful if complemented by German and Norwegian pumped-storage plants, as well as German back-up plants. To achieve a wind-solar market share of 50% in Germany, a pumped-storage volume of 0.305 TWh would be sufficient. This is just one seventh of the volume that Germany would need in autarchy and much less than the 1.401 TWh that could be made available in both countries together.

(9) Because of the non-negativity constraint, potential Norwegian pumped-storage plants are more important for Germany than the existing Norwegian hydro dams. While Germany could increase its waste-free wind-solar market share by 6.6 percentage points if it merged its grid with Norway's to participate in hydro-dam buffering, it could add another 23.7 points by receiving support from the additional pumped-storage plants that would be feasible according to the ESTORAGE project, despite the fact that the latter are tiny relative to the existing hydro dams.

(10) Adding Switzerland, Austria and Denmark to the German–Norwegian grid, while building all the pumped-storage plants the ESTORAGE project deems feasible in these five countries, would make it possible to expand the waste-free German wind-solar market share to 63% and reach a corresponding wind-solar market share of barely 50% in the five countries taken together.

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