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Buffering Volatility: A Study on the Limits of Germany's Energy Revolution

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Abstract

Based on German hourly feed-in and consumption data for electric power, this paper studies the storage and buffering needs resulting from the volatility of wind and solar energy. It shows that joint buffers for wind and solar energy require less storage capacity than would be necessary to buffer wind or solar energy alone. The storage requirement of over 6,000 pumped storage plants, which is 183 times Germany's current capacity, would nevertheless be huge. Taking the volatility of demand into account would further increase storage needs, and managing demand by way of peak-load pricing would only marginally reduce the storage capacity required. Thus, only a buffering strategy based on dual structures, i.e. conventional energy filling the gaps left in windless and dark periods, seems feasible. Green and fossil plants would then be complements, rather than substitutes, contrary to widespread assumptions. Unfortunately, however, this buffering strategy loses its effectiveness when wind and solar production overshoots electricity demand, which happens beyond coverage of about a third of aggregate electricity production. Voluminous, costly and inefficient storage devices will then be unavoidable. This will make it difficult for Germany to pursue its energy revolution beyond merely replacing nuclear fuel towards a territory where it can also crowd out fossil fuel.

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1. Germany's Energy Revolution

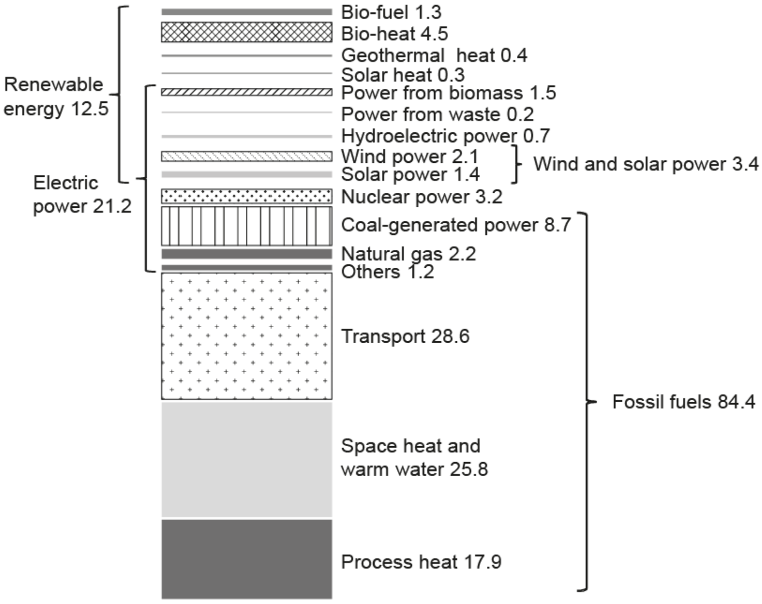
Three days after the 2011 Fukushima accident German Chancellor Merkel declared that Germany planned to abandon all of its 17 nuclear power stations, which at that time accounted for 22.2% of the country's production of electric power. After a formal exit decision was made a few weeks later, Germany began to rapidly dismantle its plants. By the end of 2015, nine nuclear plants were abandoned, a phase-out of the remaining plants scheduled for 2022.

Germany also wants to exit fossil fuel. In the Kyoto agreement the EU committed to a 8% reduction (United Nations 1998) in CO_2 emissions, and in the subsequent EU negotiations Germany 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.[1] The EU moreover wants to cut emissions by 80-95% by 2050 versus 1990.[2]

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

[1] Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (2014).
[2] European Commission (2011).

Figure 1: Germany's final energy structure (2014, %)



Calculations based on: AG Energiebilanzen (2015a, 2015b), AG 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 consumption of 2416.3 TWh. This includes final electric energy consumption, which is defined as aggregate production minus the energy sector's own consumption and minus net exports. The item "transport" only refers to fossil fuel use. The energy consumption for electric trains, which represents 0.49% of the entire final energy consumption, is subsumed under the item "electric power" and cannot be allocated to specific energy sources. The same is true for other types of electric transportation services which, however, play only a negligible role.

The figure shows that in 2014, with a share in final energy consumption of 3.4%, wind and solar power contributed about as much energy as the remaining nuclear power plants, which accounted for 3.2%. Thus, a near doubling of Germany's current wind and solar plants compared to 2014 would replace all of the country's remaining nuclear power plants, which seems like a feasible goal. This, however, would not yet constitute a contribution towards curbing the emission of fossil fuels, which account for 84.4% of Germany's entire final energy consumption and result largely from the consumption of heat in space warming and for processing purposes, as well as in transportation,

Another qualification that readers should be aware of is that the percentages mentioned refer to the entire final energy consumption rather than electricity consumption, which represents only one fifth of the total (21.2%). Thus, while wind and solar power only constitute 3.4% of the total, they account for about 16% of electricity. If we add the other green power sources shown in Figure 1, which account for nearly 12% of electric power, green power boasts a share of 27.4% of total final electric energy consumption. Other things equal, this share would rise to around 43% 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 12% of total final energy consumption, or 57% of Germany's current electric power generation. The problems arising from this endeavour will be discussed below.

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 thousand 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 – 250 meters, cannot be seen on the horizon by night. Moreover, the roofs of private dwellings all over Germany, primarily those of farm houses, 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 net prior to conventional power sources. Net companies are forced to connect even the most remote wind generators and solar panels free-of-charge:[3] 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, which was 5.74 or 6.07 cent higher, respectively, than the wholesale prices for electric power.[4] As a rule, the less efficient the appliances are, the higher prices are, so as to give all technologies a fair chance.

This truly revolutionary restructuring of Germany’s countryside has indeed resulted in a significant contribution to electric power generation, as shown in Figure 1. As mentioned, in

[3] 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).
[4] Bundesministerium der Justiz und für Verbraucherschutz (2016), European Energy Exchange AG (2016).

terms of kilowatt hours produced, 16% of electricity came from wind and solar power in 2014.

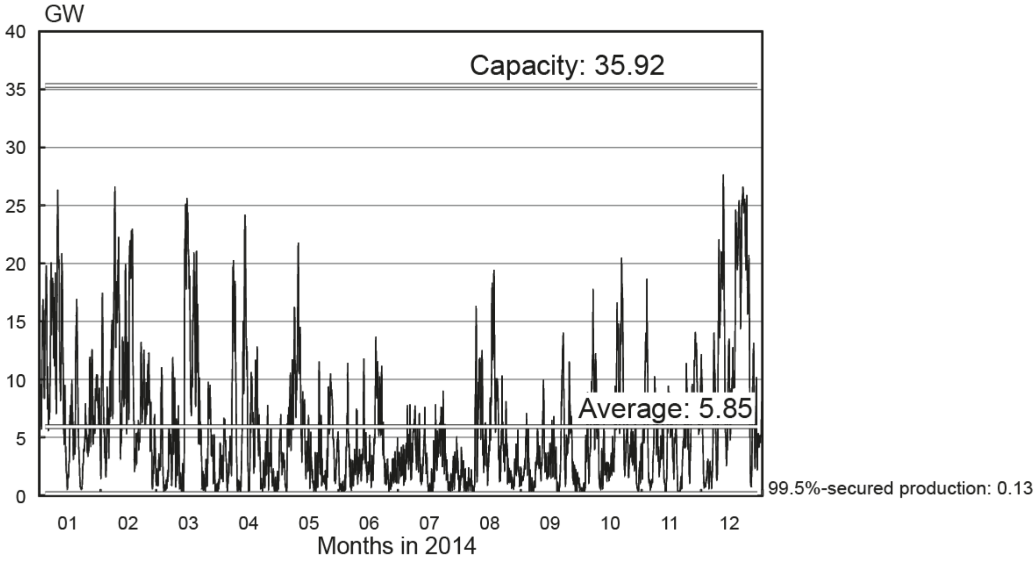
However, this impressive figure masks two fundamental problems. One is that German feed-in tariffs do not harmonise with the EU's cap-and-trade system for CO_2 emissions, which, if undisturbed, ensures a Pareto-efficient allocation of abatement effort among the power plants of Europe.[5] As that system includes the entire power generation sector, the cap determines the aggregate European emissions volume from the power sector already, and no country is able to change this volume with policy instruments that affect the composition or size of national power production. While it is true that the feed-in tariffs reduce German CO_2 emissions as they imply an injection of green power into the net and crowd out fossil fuel, they also set free fossil fuel emission rights which, at falling prices, wander through the European power exchange markets (primarily Leipzig and Amsterdam) to other EU countries. There they enable an additional volume of fossil fuel emissions exactly equal to the volume crowded out in Germany. Feed-in tariffs also discriminate against green energy production in other parts of Europe, as they lower the price of European emissions certificates and hence make fossil fuel more competitive there.[6]

The other problem relates to the volatility of wind and solar power. As impressive as the aggregate statistics are that add and relate energy from different sources, they overlook the inherent quality differences among these sources in terms of continuity and adjustability of supply.

Figure 2 shows hourly data on all German wind electricity fed into the net in 2014. The highly volatile curve gives the flow of produced electricity in terms of GW. It has been trend-adjusted to eliminate the underlying growth in installed plants during the year. On average, 24,256 plants were installed with a capacity of 1,481 kW each.

[5] For an official description, see EU Commission homepage: http://ec.europa.eu/clima/policies/ets/index_en.htm and for an economic assessment of the efficiency of cap-and-trade systems see Karp and Liu (2002).
[6] See Bundesministerium für Wirtschaft und Arbeit (2004), Bundesministerium für Wirtschaft und Technologie (2012), Weimann (2010), and Sinn (2008, 2012).

Figure 2: Wind power in Germany 2014 (24,256 plants, hourly data)



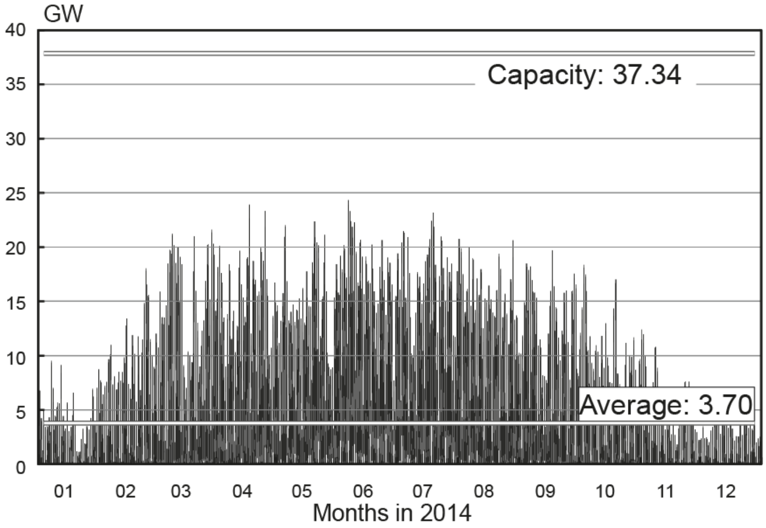
Source: Amprion, http://www.amprion.net/windenergieeinspeisung, Tennet, http://www.tennettso.de/site/Transparenz/veroeffentlichungen/netzkennzahlen/tatsaechliche-und-prognostizierte-windenergieeinspeisung, Transnet BW, https://www.transnetbw.de/de/kennzahlen/erneuerbare-energien/windenergie?activeTab=table&app=wind,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

Note: The data have been trend-adjusted to compensate for the slight growth in plant capacity over the year without changing the average.

While the overall capacity installed was 35.92 GW, the average production was 5.85 GW, just 16.3% of capacity, and the secured production which was available in 99.5% of the hours, was 0.13 GW, or just 4 per mille of capacity.

Figure 3 shows the analogue for German solar power. At 37.34 GW the average installed capacity was nearly the same as in the case of wind power. However, at 3.7 GW, the average production was only 9.9% of capacity and, of course, secured production was zero.

Figure 3: Solar power in Germany 2014 (1.5 million plants, hourly data)



Source: 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.50hertz.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: Mean preserving trend-adjusted data.

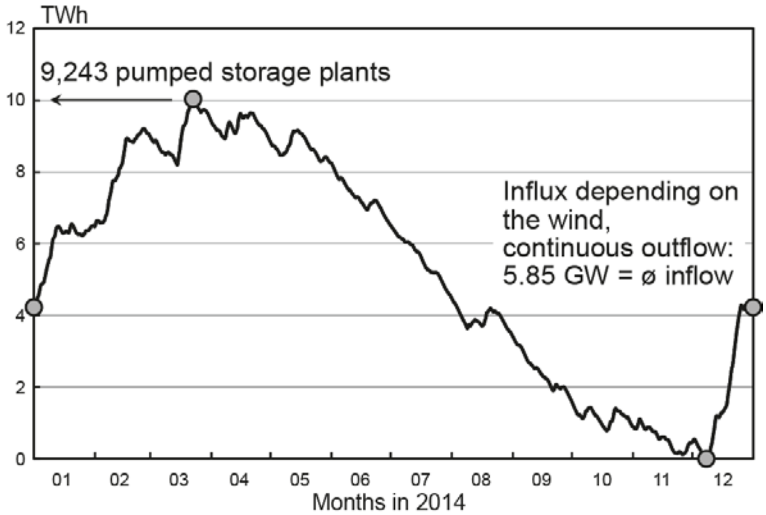
In order to make the green current usable despite its volatility, buffers are needed. The following paragraphs first study a storage strategy, assuming ideal stores that can be filled and emptied without friction. Later in the course of this paper, more realistic storage and buffering strategies will be studied. What comes closest to such ideal storage is pumped storage stations, 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 capacity of 1,077 MWh. So the total capacity of all pumped storage plants is 0.038 TWh.

Figure 4 shows the result of a thought experiment in which the actual, volatile production of wind energy is flowing into the store, while the outflow equals the average inflow, i.e. the 5.85 GW shown in Figure 2. The curve gives the stock of stored energy in terms of TWh at each point in time during the year. By construction the final stock by the end of the year is equal to the initial stock, both being chosen such that the year's minimal stock, which obviously is reached in early December, is zero. The highest point of the curve, which is reached towards the end of March, is the minimal storage volume necessary to smooth

Germany's wind power production in 2014. It stands at 9.96 TWh or 9,243 pumped storage devices of the German variety, which represents 264 times the country's actual pumped storage capacity.

This storage strategy is demanding, to say the least, particularly when public opposition from citizens' movements is taken into account. Bavaria recently tried to build an additional storage lake on Jochberg near Kochel, but had to give up this project due to severe protests by locals and the neighbouring population.

Figure 4: Storing of wind power



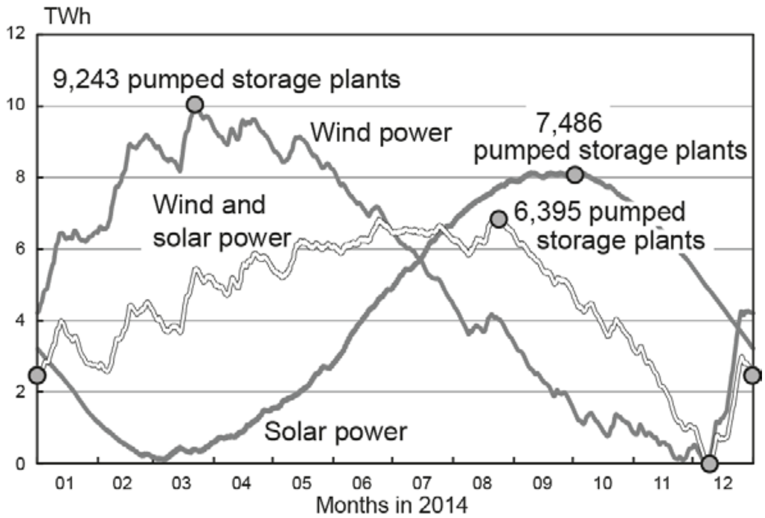
A similar calculation for smoothing solar power can be made based on the data used in Figure 3. The result is the respective storage curve shown in Figure 5 whose peak shows a required storage capacity of 8.06 TWh or 7,486 pumped storage plants of the German kind.

However, separate stores for wind and solar energy are not advisable as wind and solar power are not perfectly correlated. In fact, as a comparison of the two storage curves for wind and solar energy in Figure 5 is showing, the storage needs are negatively correlated. While wind is strong in the winter, from December to March, solar power obviously reaches its peak in the summer months. Thus, while the wind store is fullest in the second half of March (22 March 2014), as mentioned, the solar store has its maximum content in early October (4 October 2014), about half a year later. Thus, one combined store for both energy sources would certainly require less storage than two separate stores.

This is shown by the hollow curve in Figure 5, which shows the aggregate of the wind and solar storage curves. The curve was calculated by adding the wind and solar storage volumes and subtracting unnecessary storage space such that the store volume would again be zero at the lowest stock of energy stored, which is the case in early December (9 December

2014). The highest storage volume, which would be reached in the second half of August (24 August 2014) in this scenario, gives the necessary storage capacity, at 6.89 TWh or 6,395 pumped storage plants. It is remarkable that this required storage capacity is not only smaller than the sum of the separate storage capacities, but even smaller than the storage requirement for each of the two power sources.

Figure 5: Storing wind and solar power separately and jointly

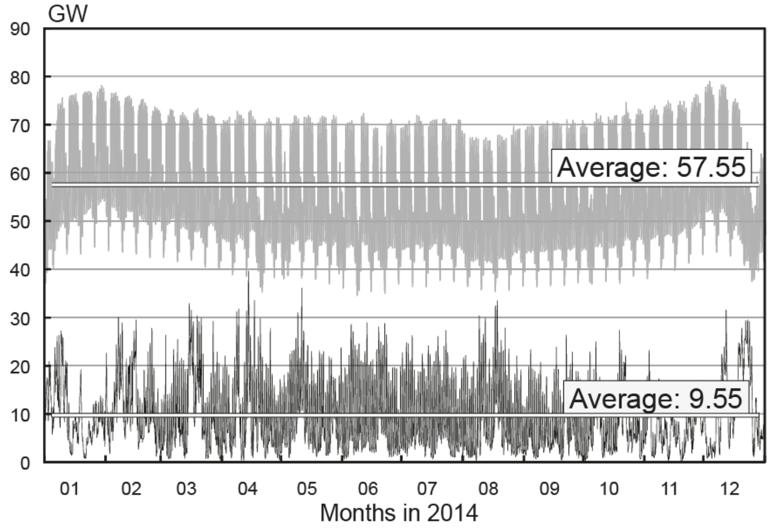


3. Volatile Demand

The next step in the analysis involves taking the volatility of consumption of electricity into account. As a strategy of buffering wind and solar power implies huge storage needs, there is some remote hope that recognition of volatile demand may lower storage requirements. After all, it is often argued in Germany that green electricity may help to "break the consumption peaks". Moreover, it is frequently pointed out that sun power is positively correlated with consumption over the course of the day.

Figure 6 dwarfs these hopes. It shows the aggregate gross (i.e. before distribution losses, but after the energy sector's own use and after net exports) hourly electricity consumption in addition to the hourly joint production of wind and solar energy. Obviously, this demand is also extremely volatile, and an eye-ball regression does not reveal any positive correlation with production that would justify optimism.

Figure 6: Wind and solar power (lower line) compared to aggregate gross power consumption (upper line)



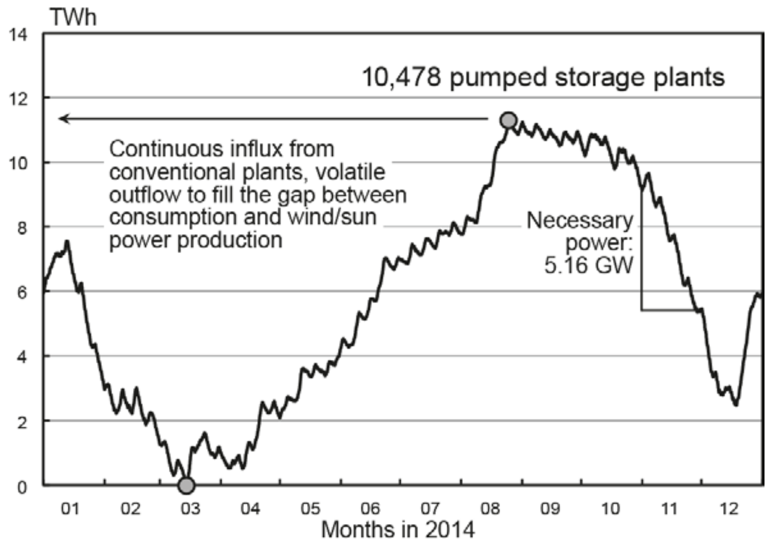
Source: European Network of Transmission System Operators for Electricity, https://www.entsoe.eu/db-query/consumption/mhlv-a-specific-country-for-a-specific-month, as well as sources given for Figures 2 and 3.

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 AG 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.

Indeed, Figure 7 reveals that there is no positive correlation between production and consumption that would reduce storage requirements. The thought experiment underlying the figure is that all conventional plants (including coal, gas, nuclear, biomass, hydro and waste, see Figure 1), produce a constant flow of energy large enough to cover the average annual difference between consumption on the one hand and production from solar and wind plants on the other. This constant flow from conventional plants is assumed to be equal to their actual average 2014 production, which stood at 48.00 GW.

The constant flow is channelled into the store, while the volatile excess of consumption over wind and solar production, which is the same on average, is taken out. 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 minimum storage size is calculated such that its volume is just sufficient to prevent the store's content from ever becoming negative. The calculations show that the lowest storage content (zero) is reached by mid-March (14 March 2014) and the highest content in late August (25 August 2014). The storage volume at the latter date, which is 11.29 TWh or 10,478 pump stores of the German kind, is the necessary storage capacity. Unfortunately, this figure is not lower, but much higher than the volume that turned out to be necessary to buffer solar and wind production (6.89 TWh) alone, as shown in Figure 6.

Figure 7: Buffering wind power, solar power and power demand with storage devices



Sometimes the size of storage devices is described as power measured in gigawatts, rather than gigawatt hours. Indeed, the question is not only how much energy can be stored, but also how quickly it can be released. Could pumped storage devices face an additional constraint in this respect?[7] The answer is given by Figure 7. The month with the steepest negative slope in the diagram is November. Here, the store's energy content falls by 3.72 TWh in the month's 720 hours, which implies a necessary withdrawal power of around 5.16 GW. As Germany's existing 35 pumped storage plants have a joint power of 6.57 GW, this obviously would not be a binding constraint. However, if all of the pump stores were emptied simultaneously so as to meet the 5.16 GW power demand, they would last just for 7 hours and 18 minutes. This shows that only capacity, or "labour" to use the physical term, and not power, is a binding constraint.

3. 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. Dish and laundry washing, as well has the use of driers could be programmed to take place during periods of ample supply and

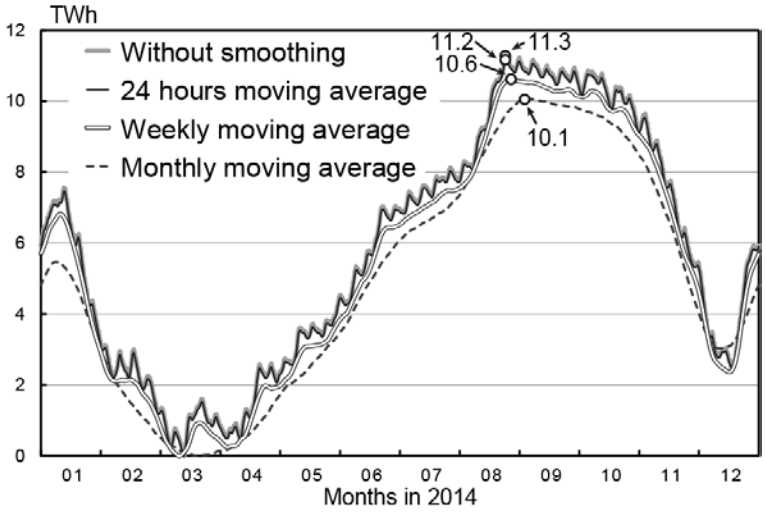
[7] For an analysis of the storage problem based on power needs, see Hack, Unz and Beckmann (2014).

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 elasticity. Even industries could shift rare, but power consuming activities to times of high supply.

Unfortunately, however, closer inspection of Figure 7 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 from summer, when everything is warm anyway. Storing dirty dishes and laundry for months before they would be washed is theoretically possible, but that would probably involve owning a closet like Paris Hilton's or cupboards as big as that of a Hilton hotel.

To assess the extent to which demand management, which absorbs the high frequencies, could possibly contribute to reducing storage space, Figure 7 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. The results are shown in Figure 8. Obviously, such short-term demand management would hardly affect storage requirements. While a storage device of 11.29 TWh would be necessary without demand management, intra-day demand management would reduce the storage requirement to just 11.19 TWh, intra-week management to 10.62 TWh and intra-month management to 10.05 TWh. Thus, instead of 10,478 ideal pumped storage lakes, 9,332 would be needed if consumption were reallocated within a month so as to coincide with green production peaks, which is still an enormous quantity compared to the 35 pumped storage plants that exist in Germany.

Figure 8: Absorbing high frequencies with demand management



4. Other Stores

Instead of calculating the required storage volume in terms of ideal pumped storage devices, it may be more advisable to use other kinds of store.[8] Arguably, the most promising alternative is methane, which is basically the same as natural gas. After all, Germany has a methane storage capacity that serves the country's gas combustion needs for several months. It is large enough to compensate for a long interruption of supply from Russia and other places. Germany has technical stores above the ground, as well as underground caverns encompassing a storage capacity of 267 TWh, which is far more than would be needed to smooth the normal volatility in German power demand and supply.[9] The problem, however, lies in converting electric power to methane and back.

The technologies for converting electric energy to methane are well-known. 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.

The conversion process, however, is inefficient and difficult. Firstly, traditional alkaline electrolysis requires a continuous input of electric power and cannot easily handle volatile inputs. Other short-term stores may therefore be needed to smooth the input, before electrolysis can begin. Secondly, methanation requires substantial supplies of CO_2, which

[8] See Sterner (2010) and Fuchs et al. (2012) for excellent overviews of the available alternatives.
[9] Bundesministerium für Wirtschaft und Energie (2015). The storage capacity is 24.6 billion m^3 and $1m^3$ is equivalent to 10.848 kWh.

may be an unwanted by-product of production processes, but cannot cheaply be delivered in a suitable form. 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.[10] 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. Moreover, taking the cost of the appliances into account, the production cost would increase multifold.

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 the Law of Carnot, which is based on the second main theorem of thermodynamics, any conversion of heat into motion energy or electric energy involves huge efficiency losses for physical reasons, quite apart from the technical reasons that add to these losses.[11]

The huge efficiency losses would increase the cost of electricity coming out of a methanation plant by a factor of three to five relative to the cost of the electric power input, even if the cost of setting up the methanation plant is disregarded. Taking the other production costs into account increases this factor further.

Even 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.[12]

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[10] 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.

[11] Thus, for example, a plant that uses vapor at a temperature of $800^{o}C$ and exhausts it at $100^{o}C$ cannot 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.

[12] 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).

Instead of methane, hydrogen could be stored. This would reduce inefficiency insofar as the energy loss on the way from electricity over a gas back to electricity would be smaller, boosting the overall efficiency by a factor of about 1.4. However, hydrogen cannot as easily be stored as methane given that it diffuses through all kinds of pipeline materials and tends to erode them. Moreover, hydrogen made from green electricity is still expensive. A kilowatt hour of hydrogen costs about six times as much as a kilowatt hour of natural methane.

Finally, some have suggested using the lithium-ion batteries of electric cars to buffer volatility. However, such batteries only have a tiny capacity. 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. Thus, one million of the Tesla's most powerful batteries would be equivalent to about 80 pumped storage plants. To buffer the volatility of Germany's 2014 wind and solar energy, as well as that of German power consumption, 125 million of Tesla’s most powerful car batteries, or 600 million BMW i3 batteries, would be needed to replace the 10,478 pumped storage plants calculated above (Figure 7). As Germany plans to have 1 million electric cars by 2020, presumably close to the BMW i3 type, and currently has a total of about 45 million cars of any kind, this is ambitious to say the least. Moreover, the cars could not be used during the winter months as they would be needed as power stores, their batteries being emptied as spring approaches.

5. Double Structures

Given all of the difficulties related to storage strategies, the reader may wonder how Germany manages to integrate its wind and solar power into its power supply. After all, the fluctuations are there already, methanation plays no role, and pumped storage devices have a miniscule capacity relative to what would be needed. The answer is that Germany uses its existing fossil plants to cushion the shocks resulting from inserting wind and solar energy into the net. In fact, the difference between the consumption and production curves in Figure 6 is being compensated for with conventional production in Germany and international trade, which shifts some of the volatility abroad and forces other countries to act as shock absorbers. While exports net of imports of electric power on average accounted for 6.6% of final German energy consumption in 2014, exports alone stood at 14.5% and imports at 7.9% of overall consumption.[13] 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 and power pikes are exported to other countries. When

[13] Arbeitsgemeinschaft Energiebilanzen e. V., Energiebilanz 2014.

there is no wind and sunshine, by contrast, conventional plants and imports are used to fill the energy gaps.

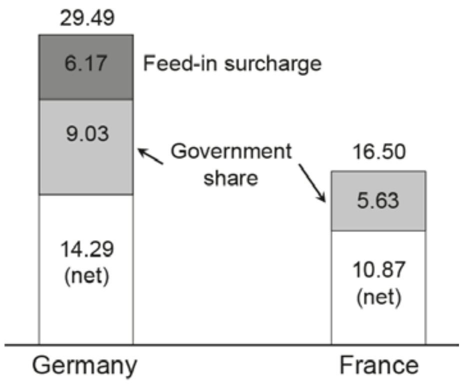
Gas power plants are most useful for buffering short-term fluctuations, but as these plants produce rather expensive electricity, most of the buffering is done by hard coal power plants. It is true that such plants cannot react as quickly as gas plants to fluctuating demands. Intra-day fluctuations are 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 Figures 7 and 8. Thus coal and methane stores that are refilled from mines and natural sites serve as 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.[14]

While the German buffering strategy to date has worked without invoking a black-out in the net, it is extremely expensive and inefficient, as it involves double structures with double costs. It is no wonder that electricity is very expensive in Germany. Figure 9 compares German and French electricity costs per kWh for final household consumers. It shows that German consumers pay roughly twice as much as their French counterparts.

[14] F. Vahrenholt in a Lecture at the Bavarian Academy of Science, January 2012, reported 10 minutes.

Figure 9: Electric Energy Prices for Domestic Consumers[1)] in Germany and France in 2015 (ct/kWh)



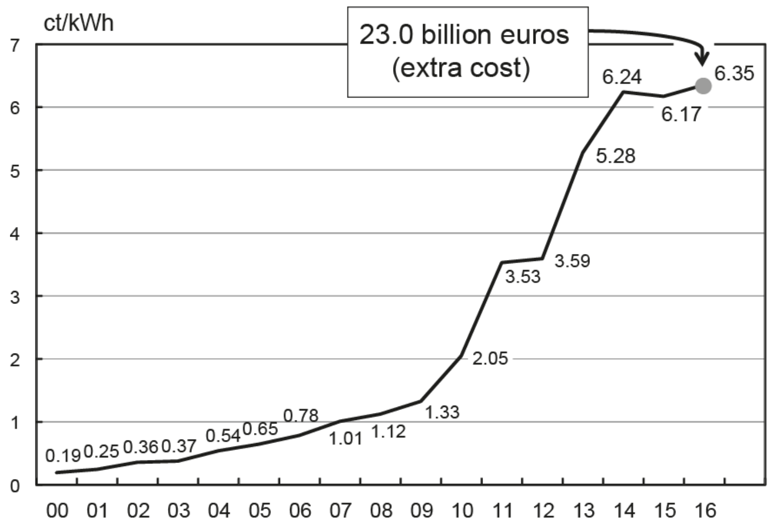
1) Average of 1st and 2nd half-year; Consumption between 2,500 kWh and 5,000 kWh per year.

Source: 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.

The high cost of electricity in Germany partly results from the differing wholesale prices of electric power 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. In 2015, this surcharge was 6.17 cent per kWh.

Figure 10 shows the time path of the feed-in surcharge since the introduction of the respective law (Erneuerbare-Energien-Gesetz, EEG). While the surcharge was miniscule initially at only 0.19 cent per kWh, it has grown exponentially because the incentives it provided have induced a massive expansion of green energy. In 2015, this growth ground to a halt, as the German government reduced feed-in tariffs, but in 2016 the surcharge rose again to 6.35 cents. In absolute terms this represents a subsidy for green energy of 23 billion euros, which is about a hundred times the sum Germany gives the Max-Planck Institute in Greifswald to run a rather successful experimental nuclear fusion reactor.

Figure 10: The German feed-in surcharge



Source: Fraunhofer ISE, Kurzstudie zur historischen Entwicklung der EEG-Umlage, Figure 1; since 2010: Netztransparenz.de, Erneuerbare Energien Gesetz, EEG-Umlage.

As mentioned above, the feed-in tariffs thanks to which the German solution has been enforced are unable to reduce European CO_2 emissions, given that these emissions are already defined by the EU's cap & trade system. Germany's efforts merely serve to make the emission rights cheaper, thus relocating emissions from Germany to other EU countries and undermining the chances of green technologies being developed there. Thus the only rationale for adding even more wind and solar energy to the German energy mix than the emissions trading system itself would already have implied, while maintaining the fossil fuel generators as shock absorbers, could be its profitability from a business economics perspective. However, there are no indications that such profitability will be achieved in the foreseeable future, as this would require the *marginal* cost of producing electricity from fossil fuels to exceed the *average* cost of producing wind and solar energy. 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.[15] By contrast, the feed-in tariffs for electricity from new wind and sunlight plants, which presumably are just large enough to cover the average cost, are about 9 cents per kWh, as was mentioned above.

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

6. The Limits of the German Strategy

While the German strategy of buffering the volatility of green electric power with conventional plants is working for the time being, it faces obvious limits when the production peaks overshoot consumption, given that conventional plants can at best be driven down to zero production and are unable to produce a negative output.

As Figure 6 above suggests, such a point had not been reached until 2014. In each and every hour of the year 2014, power demand exceeded wind and solar power production. However, in March, April and August there were obviously times when the upward production spikes came close to the downward demand spikes.

In fact, the situation was far more complex than the graph suggests. Although perfectly flexible conventional plants would have been able to buffer the volatility, there were many hours in the year when the spot price of electricity was negative, because conventional plants could not be shut down fast enough to compensate for sudden wind and solar peaks.[16]

The surplus power was then often unloaded to the nets of other EU countries at negative prices. The German government praises the country's power exports due to the increase in green electricity on its website,[17] but it forgets to mention that for some of the exports Germany was paying, rather than receiving money. Thus, while it was true that Germany was physically exporting electric power to other countries, in many cases it was in fact importing a service: the service of waste abolition, because waste is what the green surplus power had become.

Other European countries, such as Poland or the Czech Republic, have complained about the destabilising power spikes arriving from Germany through international power lines forcing them to buffer German volatility by running their coal power plants adversely to the sun and wind available in Germany. They now plan to install phase shifter transformers at the borders to block the transportation of unwelcome German power, and indeed Poland has begun to build such a device.

German power grid companies, which are legally forced to absorb green electricity as a priority, have reacted to the negative prices by even asking wind turbine owners to stop producing, but nevertheless paying them up to 90% of the administered feed-in tariffs on their potential production. Activists argue that in 2015 they paid nearly 600 million euros to wind turbine owners to stop their generators and not produce electric power, although enough wind

[16] Between December 2013 and December 2014, the German energy market had 97 hours at negative spot prices, where the average price per kWh was – 4.1 cent. See Götz, Henkel, Lenck and Lenz (2014).

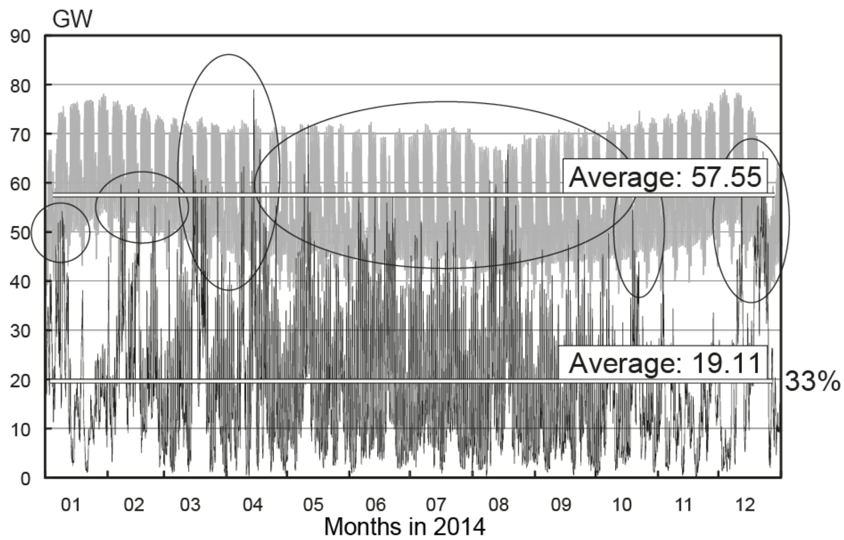
[17] See Deutsche Bundesregierung (2014).

was available.[18] Such difficulties will increase if Germany continues its way towards green energy autarchy as intended.

The rest of this paper is devoted to a discussion of the efficiency of the double-structure buffering strategy should the production of wind and solar energy be gradually expanded, covering larger and larger shares of the German consumption of electric power. 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. Thus, an expansion of production will proportionally expand the production curve shown in Figure 6 including its mean and standard deviation. In the absence of any clues as to how to predict weather changes in the years ahead, the analysis takes the year 2014 as an example.[19] If anything, global warming looks set to make the weather more volatile and result in more pessimistic conclusions than those reported here.

Figure 11 shows the result of a doubling of wind and solar power relative to 2014, bringing the share of this energy up to 33% of aggregate output, which would mean (see Figure 1) that even the remainder of Germany's nuclear power plants could be closed. As can be seen, some of the production pikes would then 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 other countries were to absorb the volatility in its energy supply.

Figure 11: Doubling German production of wind and solar energy relative to 2014



[18] See http://www.niederlausitz-aktuell.de/brandenburg/item/61413-bvb-freie-waehler-unterstuetzen-volksbegehren-gegen-windkraft-im-wald-und-ueberteuerte-strompreise.html.

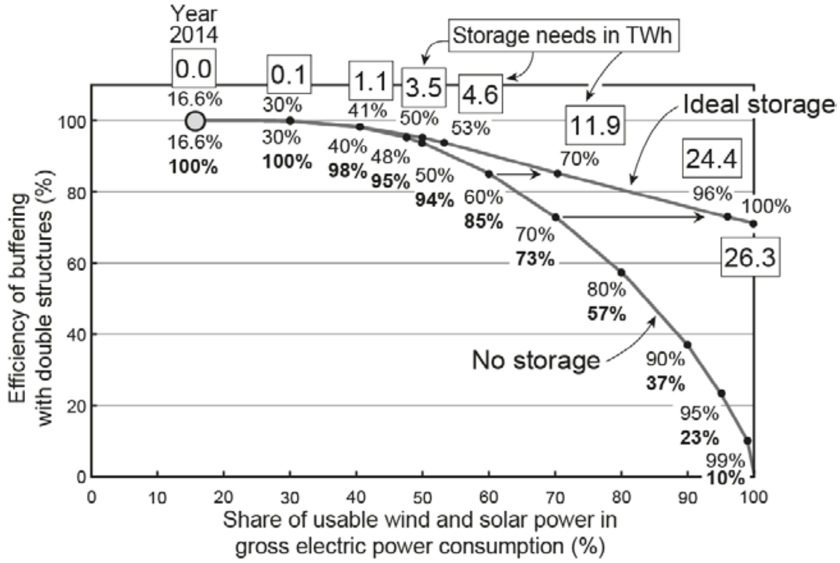
[19] Analyses of previous years already conducted by the author did not generate qualitatively different results as the year 2014 was not characterised by unusual weather conditions.

If higher shares of wind and solar energy are to be fed into the net, the surplus production would either have to be wasted, buffered by stores of the kind discussed above, or exported. The following discussion abstracts from the volatility of exports and imports, as the growing resistance apparent in the negative energy prices and the building of phase shifter transformers makes it wise for Germany to find strategies that would avoid using neighbouring nets as shock absorbers.

Figure 12 shows the result of a series of alternative calculations that aim to assess the technical efficiency of the double-structure-cum storage strategy, defined so as to buffer as much as theoretically possible with (perfectly flexible) conventional power plants and smoothing the surplus pikes by energy stores along the lines studied above. To be specific, only the surplus power is channelled into a store from which a continuous flow equal to the average annual flow of surplus power is withdrawn and fed into the net. The store's volume then changes over the course of the year in a similar way as shown in previous graphs in this article (e.g. Figures 4, 5 or 7), and by construction the store's end-of-year energy content is equal to its content by the beginning of the year. The calculations aim to find the minimum storage capacity sufficient to prevent the store's lowest content from becoming negative by using the method described above. For the moment, this store is assumed to be available without technical or physical efficiency losses.

The graph 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 refers to the case without storage, i.e. where all buffering comes from adjusting conventional production and overshooting spikes are wasted. The right curve shows the market share resulting from buffering the overshooting spikes with ideal stores. The 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. If this efficiency is enhanced by perfect, frictionless stores, the waste can be avoided and usable production is 100%. This increases the market share of wind and solar power and shifts the production curve to the right.

Figure 12: Efficiency losses from buffering with conventional plants and necessary storage volume for overshooting production spikes



Legend: The diagram shows the efficiency of wind and solar energy resulting from the double-structure strategy as a function of the 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 net, increasing the share of wind and solar power in total power consumption. The figures in the boxes above the right-hand curve give the respective necessary storage volume in terms of TWh. 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.

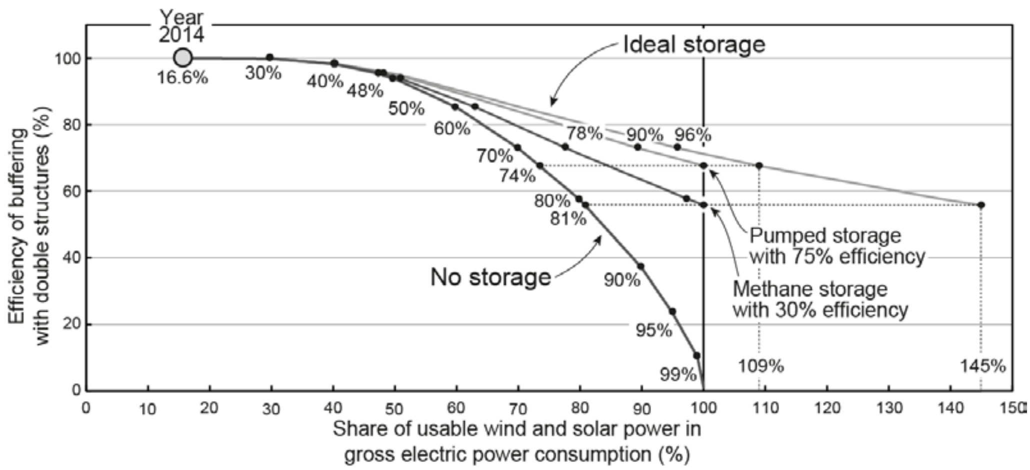
The small boxes above the curves show the respective storage space required in TWh. The (light) percentage figures above the right-hand and directly below the left-hand curve give the respective market shares in overall energy consumption covered by wind and solar energy, and the bold percentage figures below the left-hand curve indicate the efficiency resulting from the double-structure strategy alone. Some further details are spelled out in a legend below the diagram. As, by assumption, the overall efficiency resulting from the double-structure-cum-storage strategy is 100%, the horizontal distance between the two curves is the potential efficiency gain from storage.

As the figure shows, Germany's current strategy of buffering the volatility of wind and solar energy with double structures alone becomes increasingly ineffective once the wind and solar market accounts for more than a third of total energy production (cf. Figure 11). Beyond that fraction, the efficiency curve progressively bends downward. If, for example, a market share for wind and solar power of 50% is to be achieved, the production before waste would have to be 53% of aggregate power consumption. Thus the efficiency of the double-structure strategy is 94% (= 50%/53%), and 6% of wind and solar production would have to be wasted in this case.

Let us suppose, on the other hand, that a 50% market share is to be achieved by combining double-structure buffering with perfect storage, which would increase the overall efficiency to 100%. The required storage volume would then be 3.5 TWh. It would add two percentage points to a market share of 48% that a double-structure strategy alone would have supplied. The required storage volume is substantially lower than the 11.29 TWh storage that would be needed to smooth Germany's 2014 excess of consumption over its wind/solar production (with a market share of 16%). However, the required storage space still is about 93 times the storage volume (0.038 TWh) that Germany's 35 pumped storage plants currently provide.

While ideal, frictionless stores have been assumed in this paper to date, Figure 13 extends the analysis to more realistic assumptions about energy losses resulting from the storage detour. Pump stores with an efficiency of 75% and methane stores with an efficiency of 30% are assumed, as discussed above in Section 4. The technical efficiency losses imply that the market shares associated with the alternative efficiency levels of the double-structure strategy alone, as measured at the ordinate, shrink relative to ideal storage. Thus, for example, an efficiency of the double-structure strategy of 73%, which would lead to a market share for wind and solar energy of 70% if no stores were available, could be boosted to a market share of 78% if supported by methane storage and to a market share of 90% if supported by pump stores, while the theoretical market share of 96% shown in Figure 12 could never be reached. More details on the calculations underlying Figures 12 and 13, as well as the required storage space are given in the appendix.

Figure 13: Efficiency losses and wind/solar market shares of a double-structure-cum-storage strategy with alternative kinds of stores



The ideal-storage and pumped-storage curves are extended to the range of a market share beyond 100% to demonstrate the role of the technical efficiency losses resulting from storage. The graph shows, for example, that a market share of 100% reached by combining double-structure buffering with methane storage requires a wind and solar production equal to 145% of demand. Similarly, it indicates that a market share of 100% reached by combining double-structure storage with pumped storage plants requires wind and solar production to be 109% of demand. Hence the excess production of 45% or 9%, respectively, is the waste resulting from technical and physical efficiency limits characterising these alternative double-structure-cum-storage strategies.

7. Concluding Remarks

While mankind hardly has any alternative to replacing fossil fuels with energy sources that do not contribute to global warming, this paper has demonstrated the difficulties resulting from Germany's attempt to simultaneously replace both nuclear power and fossil power with solar and wind energy. The enormous volatility of wind and solar power poses a problem that is often overlooked. During some periods of the year, there is hardly any wind and solar energy available in Germany, while at other times the production is nearly as great as aggregate power demand. Thus, a strategy of buffering the volatility with energy stores seems to be a reasonable solution.

However, the storage volume required to implement this strategy would be huge. Smoothing Germany's 2014 wind and solar energy production would require a storage volume of around 7 TWh or 6,400 pumped storage plants of the German variety, whereas Germany currently only has 35 such plants.

Sometimes it is argued that wind and solar energy could help break the "consumption peaks", suggesting that the volatility problem can be handled more easily if demand fluctuations are also taken into account. However, detailed calculations dwarf this hope. A storage capacity of 11.29 TWh, equivalent to 10,478 pumped storage plants, would have been necessary to absorb both the demand and the supply fluctuations seen in 2014.

Another argument is that intelligent demand management could mitigate the problem. However, as Figure 8 showed, this is not really true. Smoothing short term variations during a day, a week or a month would reduce the storage capacity required by just 0.9%, 6% or 11%, respectively, because storage requirements result from seasonal, rather than short-term variations. The stores would be full in August/early September and emptied during the winter up to March. It is hardly conceivable that intelligent demand management could bridge such a long time span.

Thus, buffering the volatility from wind and solar energy with double structures, i.e. basically maintaining the fossil fuel plants and letting them run at variable power so as to compensate for volatile demand and wind/solar supply fluctuations, seems to be the only reasonable strategy. This option, which has actually been adopted in Germany, makes fossil fuel plants complements to, rather than substitutes for, green plants as is commonly assumed. This fact not only implies double fixed costs, which have turned Germany into a country with extremely high energy costs, but it may also force economic model builders to reconsider their assumptions about back-stop technologies.

A major problem with the German approach is that the priority feed-in rights of green energy render traditional plants unprofitable, given that they can only be used part-time. While some may argue that this is a natural and desired implication of Germany's green energy revolution, it is important to realize that Germany's greening strategy can only work if the fossil substitute plants remain intact to serve as gap-fillers. To date Germany has not yet introduced a pricing scheme that would compensate the owners of traditional power plants for offering their flexibility service. If it did, its energy costs would increase even further.

Regardless of this economic difficulty, the German strategy of buffering the volatility with double structures will reach its natural limits when the wind and solar production pikes begin to overshoot demand. It follows from Figures 1, 11 and 12 that this will be the case when this type of green energy has replaced all remaining nuclear power plants in Germany and stands at about one third of aggregate electric power production. Moving beyond this point is necessary to make a contribution to curtailing fossil fuel production, but it means entering a range of progressively declining returns, as the overshooting production pikes comprise an increasing fraction of output, which will either have to be wasted or smoothened through stores. As was shown, reaching an overall 50% share of wind and solar energy in the entire production of electric power would require 3.5 TWh of ideal storage capacity, which is about a hundred times (93 times) the capacity of pumped stores currently available in Germany.

More realistic storage options involve the production of methane from electric power, which can then be stored, and a reproduction of electric power by burning the methane in gas turbines. However, the methane storage strategy destroys between two thirds and four fifths of the energy input, and also requires complicated and expensive appliances. It is true, the storage need as such is not a problem. For one thing, the efficiency loss reduces the energy to be stored, and for another, methane storage space is amply available. However the round trip via methane involves huge efficiency losses and costs. Producing only hydrogen by way of electrolysis and storing the hydrogen is a little less inefficient than using methane, but the advantages are not that obvious if the difficulties in handling and transporting hydrogen are taken into account.

Given all these difficulties, it will be worthwhile for the world community to carefully observe the outcome of the German experiment before mimicking it by also dismantling its nuclear power plants.

Appendix

Overall efficiency and wind/solar market shares for alternative double-structure-cum-storage scenarios

Table 1 provides a more extensive overview of the numerical results used to calculate Figures 12 and 13. The first main column shows alternative market shares of wind and solar energy and the associated degrees of efficiency of the German double-structure strategy without using additional stores. The second main column shows i) the market share, ii) the degree of efficiency of the double-structure-strategy as such and iii) the necessary volume of an ideal, frictionless store, as incorporated in the right-hand curve of Figure 12 and the outmost right-hand curve in Figure 13.

The most important information is contained in the third and fourth main columns, which refer to a more realistic modelling of pumped storage and methane storage with their respective assumed "round-trip" efficiency figures of 75% and 30%, respectively.

Table 1: Efficiency of alternative double-structure-cum-storage strategies

No storage		Ideal storage			Pumped storage[1)]			Methane storage[2)]		
Market share	Efficiency	Market share	Efficiency	Required storage (TWh)	Market share	Efficiency	Required storage (TWh)	Market share	Efficiency	Required storage (TWh)
16.6%	100.0%	16.6%	100.0%	-	16.6%	100.0%	-	16.6%	100.0%	-
30.0%	99.9%	30.0%	100.0%	0.1	30.0%	100.0%	0.1	30.0%	99.9%	0.1
40.0%	98.3%	40.7%	100.0%	1.1	40.5%	99.6%	0.9	40.2%	98.8%	0.7
47.6%	95.2%	50.0%	100.0%	3.5	49.4%	98.8%	2.8	48.3%	96.7%	2.1
50.0%	93.8%	53.3%	100.0%	4.6	52.5%	98.5%	3.7	51.0%	95.7%	2.8
60.0%	85.2%	70.4%	100.0%	11.9	67.8%	96.3%	9.6	63.1%	89.6%	7.1
70.0%	72.9%	96.0%	100.0%	24.4	89.5%	93.2%	19.8	77.8%	81.0%	14.6
71.2%	71.2%	100.0%	100.0%	26.3	92.8%	92.8%	21.3	79.8%	79.8%	15.8
73.6%	67.7%	108.8%	100.0%	30.3	100.0%	91.9%	24.0	84.2%	77.4%	18.2
80.0%	57.4%	139.3%	100.0%	44.5				97.8%	70.2%	26.7
80.9%	55.9%	144.7%	100.0%	53.6				100.0%	69.1%	28.2

1) 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).

2) Methane storage "round-trip" efficiency of 30%, composed of 60% input (electric power to methane) and 50% output (methane to electric power) efficiency.

A comparison of the columns reveals, for example - as is also illustrated in Figure 13 - that the market share of wind and solar power could be increased from 70% to 89.5% with 19.8 TWh pumped storage capacity. This would involve 18,351 pumped storage plants of the German variety, 524 times the number Germany currently has. The overall technical efficiency of the entire wind and solar based production process would accordingly be raised from 72.9% (double structure, no storage) to 93.2% (double-structure-cum-pump-storage). If, on the other hand, only methane stores with a capacity of 14.6 TWh became available for the same number of wind and solar plants, the market share could be raised from 70% to 77.8%, and overall efficiency would be raised from 72.9% to 81.0%. The reader may find other interesting constellations.

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