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BUFFERING VOLATILITY:
A STUDY ON THE LIMITS OF GERMANY'S ENERGY REVOLUTION

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

Based on the 2014 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, focusing on a "double-structure-cum-storage strategy". While buffering wind and solar energy jointly requires less storage capacity than buffering them separately, joint buffering requires a storage capacity of over 6,000 pumped-storage plants, which is 183 times Germany's current capacity. Taking the volatility of demand into account would not reduce storage needs, and managing demand by way of peak-load pricing would only marginally do so, given that storage is primarily needed for seasonal fluctuations. Thus, only a buffering strategy based on double structures, i.e. conventional energy filling the gaps left in windless and dark periods, seems feasible. With this strategy, green and fossil plants would be complements rather than substitutes, contrary to widespread assumptions. Unfortunately, however, a buffering strategy based on double structures loses its effectiveness when wind and solar production overshoots electricity demand. This is shown to happen when average wind and solar power production exceeds about one third of aggregate electricity production. Voluminous, costly and inefficient storage devices will then be unavoidable to avoid progressively increasing efficiency losses. Buffering the overshooting production spikes associated with a market share of wind and solar of 50% would require an ideal, frictionless storage volume of 2.5 TWh or a storage capacity of 2.1 TWh in ordinary pumped-storage plants. This is about seven times the entire pumped-storage capacity currently available in western Europe, including Norway and Switzerland; and 81% of the volume that the EU's ESTORAGE project considers as "realisable" in western Europe. This will make it difficult for Germany to pursue its energy revolution towards green autarchy, as intended.

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1. Germany's Energy Revolution

With a share of 16% in total final energy production, Germany is one of the most advanced countries in the world in terms of power generation from wind and solar energy. The country places great hope in this kind of green energy production to gradually replace both fossil and nuclear energy in the future. However, the statistics blur the fact that wind and solar energy is an extremely volatile and inflexible power source, and hence of much lower quality than the stable and adjustable flow of energy from conventional sources. The volatility of wind and solar energy poses substantial problems for grid stability, which can only be solved with expensive buffering strategies. Based on hourly production and consumption data for Germany in 2014, this policy paper studies the buffering possibilities and discusses their limits to enable the rest of the world to learn from the German experience.

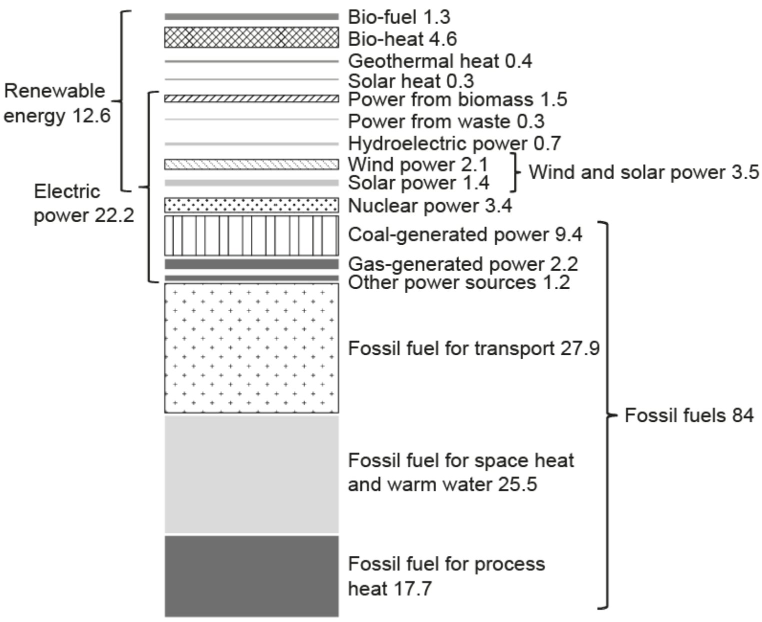
Germany's green energy revolution has been underway for two decades, but accelerated substantially after the 2011 Fukushima accident, as Germany reacted with the decision to abandon all of Germany's 17 nuclear power stations, which at that time accounted for a good fifth of the country's production of 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 a 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.[1] The EU also wants to cut emissions by 80-95% by 2050 versus 1990.[2]

The double exit from nuclear and fossil energy is ambitious. The dimensions of this task are illustrated in Figure 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).

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

Figure 1: Germany's final energy production (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 production of 2450.2 TWh by source. Final energy production is defined as aggregate production minus the energy sector's own consumption.

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 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. 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 in transportation.

A qualification that readers should be aware of is 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 Figure 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 meters, 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.[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.

While Germany's achievements are impressive, there are 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, generates a uniform price for carbon that ensures an efficient, cost-minimizing allocation of abatement efforts among the power plants of Europe. As the cap already determines the aggregate European emissions volume from the power sector, additional national measures that affect the composition or size of national power production will necessarily lead to an inefficient allocation of abatement measures

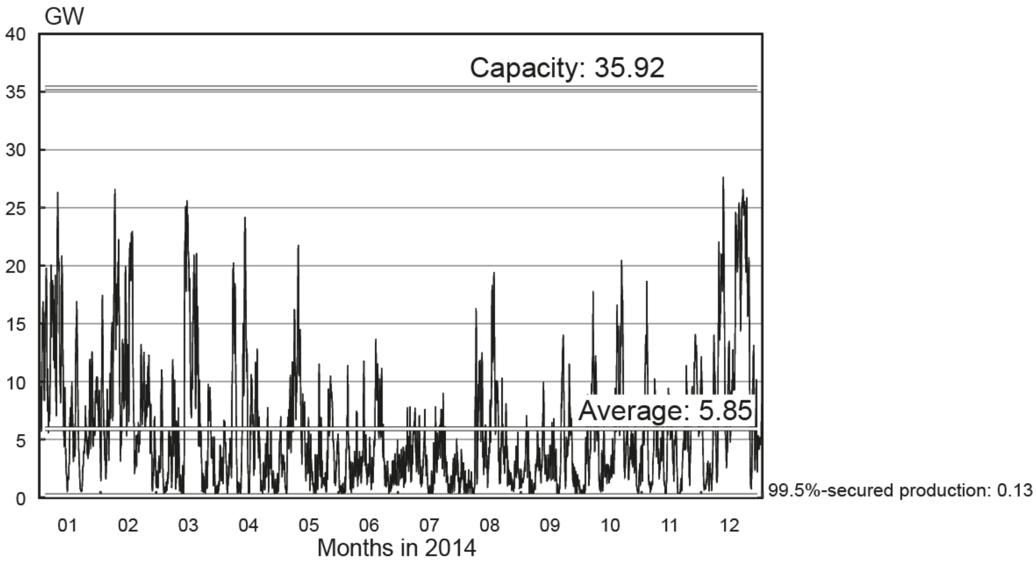
[3] According to Ferroni and Hopkirk (2016), the investment necessary to connect remote locations consume so much energy that solar panels become energy sinks instead of serving as energy sources. Cf. also Trainer (2014).
[4] Bundesministerium der Justiz und für Verbraucherschutz (2016), European Energy Exchange AG (2016).

across the participating countries.[5] Moreover it will not be able to change the aggregate emissions other than by changing the cap itself through public-choice effects.[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 grid 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 production capacity of 1,481 kW each.

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.

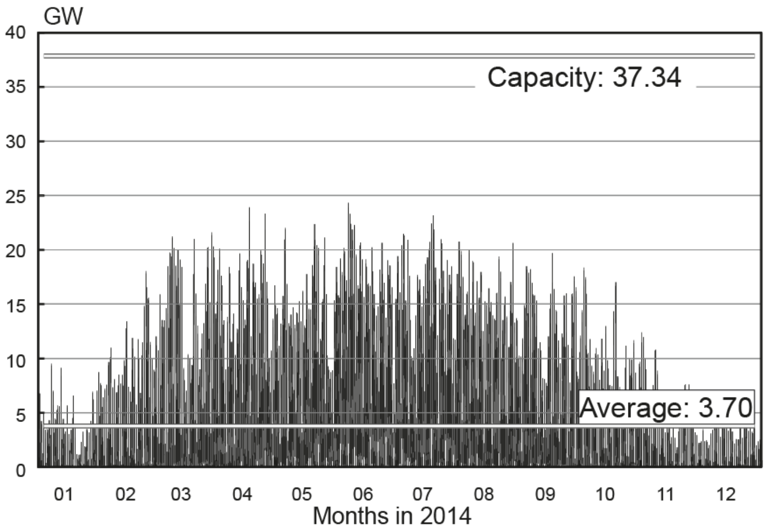
Note: The data have been trend-adjusted to compensate for the slight growth in plant capacity over the year without changing the average.

While the overall production capacity installed 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 just 4 per mille of capacity.

[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 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)



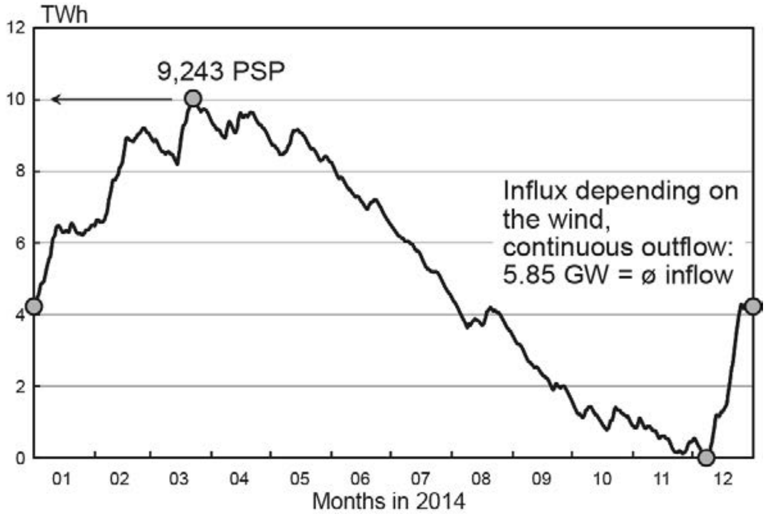
Source: Amprion, http://www.amprion.net/photovoltaikeinspeisung, Tennet, http://www.tennettso.de/site/Transparenz/veroeffentlichungen/netzkennzahlen/tatsaechliche-und-prognostizierte-solarenergieeinspeisung_land?lang=de_DE, Transnet BW, https://www.transnetbw.de/de/kennzahlen/erneuerbare-energien/fotovoltaik, 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 buffering strategies will be studied, based on storage and double structures. 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 MWh. So the total volume 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 steady outflow equals the average inflow, i.e. the 5.85 GW shown in Figure 2. The assumption of a steady, non-volatile outflow is made here and in the next few pages to ensure that wind power is able to replace conventional base load power sources without imposing additional buffering needs on other conventional sources remaining operative, which would reduce their degree of capacity utilization and hence business profitability. Other buffering strategies will be discussed later. The curve gives the volume of stored energy in terms of TWh at each point in time during the year. 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 minimal volume, 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.

Figure 4: Storing of wind power

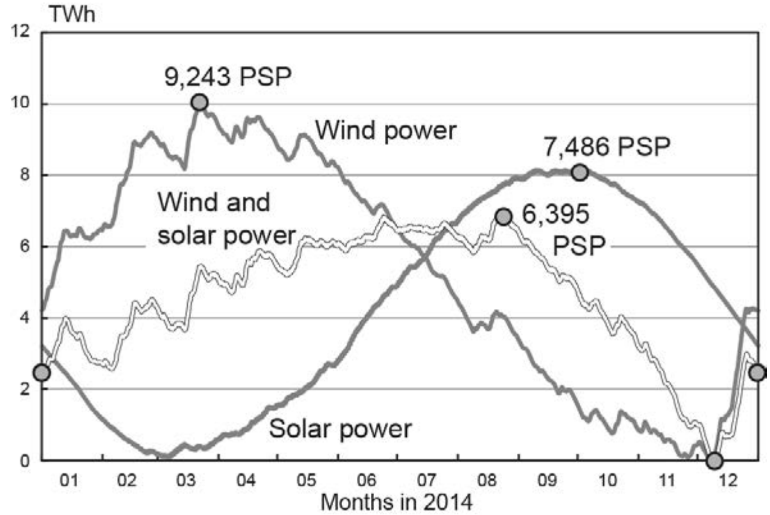


A similar calculation for smoothing solar power can be made based on the data used in Figure 3. The result is the respective solar storage curve shown in Figure 5 whose peak gives a required storage volume of 8.06 TWh or 7,486 pumped-storage plants of the German kind.

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 shows, 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.

The hollow curve in Figure 5 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 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), gives the necessary storage size, at 6.89 TWh or 6,395 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 even smaller than the storage requirement for each of the two power sources.

Figure 5: Storing wind and solar power separately and jointly



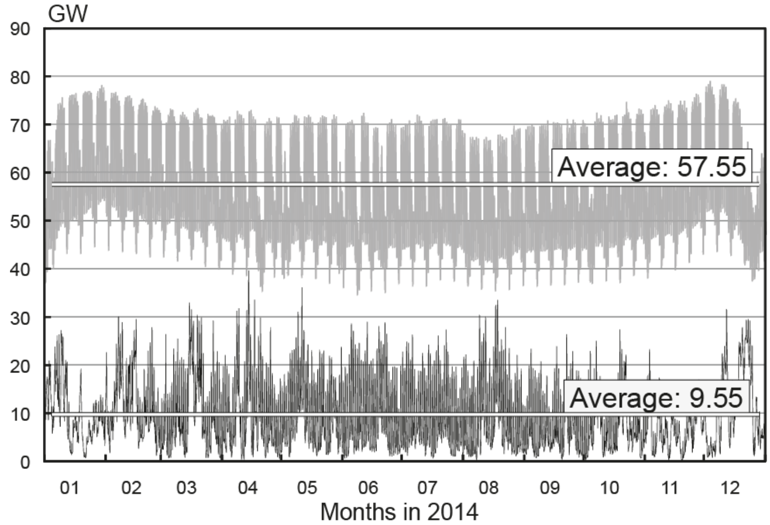
Complementary information can be gained by taking a look at statistical data. While the variance of wind power production in 2014 was $2.95*10^{19}\ W^2h^2$, the variance of the solar power production was $3.06*10^{19}\ W^2h^2$, and the variance of wind and solar production together was $5.07*10^{19}\ W^2h^2$. 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. [7] 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 Figure 5 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.

[7] Similar observations have been made by Heide, von Bremen et al. (2010) in a study based on regional wind speed and solar radiation data for Europe.

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. Figure 6 looks into this issue.

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.

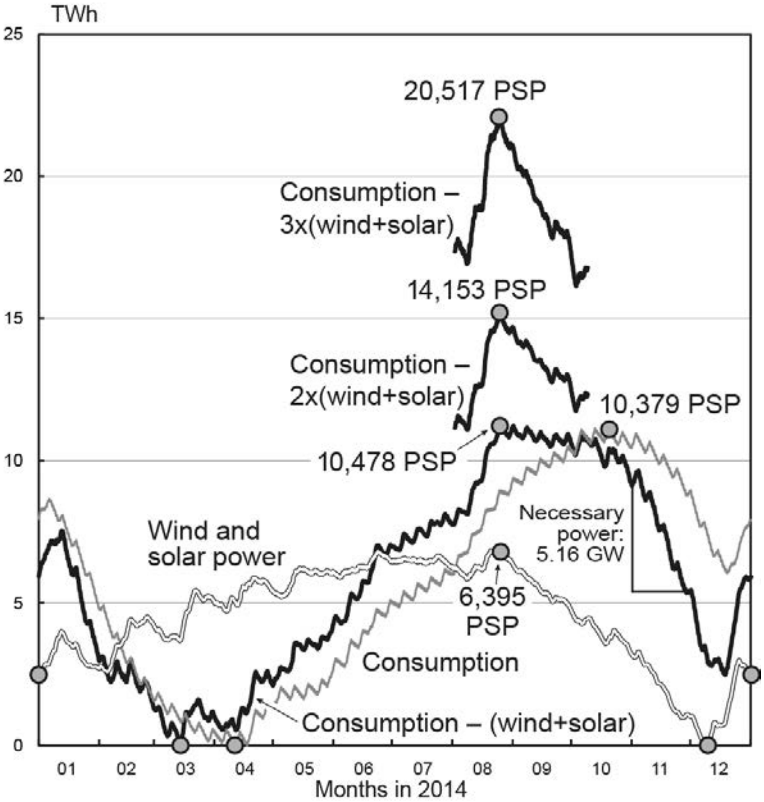
Note: Trend-adjusted data for wind and solar production. The Euro Network consumption data refer to consumption before distribution losses. They are not fully compatible with the AG Energiebilanzen data used in Figure 1 and result in a slightly higher share of wind and solar energy (16.6% instead of the 16% mentioned there). Cf. https://www.entsoe.eu/Documents/Publications/Statistics/20150531_MS_guidelines_public.pdf.

Figure 6 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. With a value of $1.08*10^{20}$ W^2h^2 the variance of consumption is more than twice as large as the variance of wind and solar power, which stands at $0.507*10^{20}$ W^2h^2. Interestingly, however, with a value of $1.14*10^{20}$ W^2h^2 the variance of the difference between consumption and wind-solar energy is only slightly greater than the variance of consumption alone, which indicates a sizeable positive correlation among the series. Indeed, the correlation coefficient is +0.30. This is good news insofar as it suggests that integrating wind and solar energy at its current level into the German grid only slightly increases the overall volatility of the system.

This impression is confirmed by a more relevant calculation of the storage needs as is given in Figure 7. The figure repeats the wind-solar storage curve of Figure 5 (hollow curve), the storage curve for demand smoothing alone (grey curve) and the curve for smoothing both supply and demand (solid curve).

Let us first consider the demand storage curve (grey). The thought experiment underlying this curve is that the 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 capacity is the store's maximum volume resulting from an initial volume that empties the store for at least one hour. The calculations show that the lowest storage content (zero) is reached by April (11 April 2014) and the highest content in October (20 October 2014). The storage volume at the latter date, which is 11.180 TWh or 10,379 pumped-storage plants of the German kind, is the storage capacity required to smooth power demand.

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



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 Figure 1) produce a constant flow of energy large enough to cover the average annual difference between volatile consumption, on the one hand, and volatile 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. Otherwise, the calculations follow the same logic as above. The calculations show that the combined store is empty by mid-March (14 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 or 10,478 pumped-storage plants of the German kind, is the necessary storage capacity. This figure is much higher than the volume that turned out to be necessary to buffer solar and wind production (6.89 TWh or 6,395 PSP) alone, as was shown in Figure 5, but obviously only a little (99 pumped-storage plants) higher than the 11.18 TWh or 10,379 pumped-storage plants needed to smooth consumption. Thus, the integration of wind and solar power at their current volumes into the German net 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.[8] Thus, an expansion of production will proportionally expand the production curve shown in Figure 6, including its mean and standard deviation. As illustrated by the two peaks above the point of maximum storage, a doubling and tripling of Germany's current wind and solar plants at identical locations would strongly increase the storage needs way beyond the 2014 figures, to 14,153 and 20,517 pumped-storage plants, respectively. Tripling Germany's current wind and solar production would imply that roughly half (48%) of its electric power supply was generated by wind and solar power.

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 can be released. Could pumped-

[8] 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.

storage devices face an additional constraint in this respect?[9] The answer is given by the triangular slope measure in the right-hand region of Figure 7. 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. Dish and laundry washing, as well as the use of driers could be programmed to take place during periods of ample supply and 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 non-frequent, but power consuming activities to times of high supply.

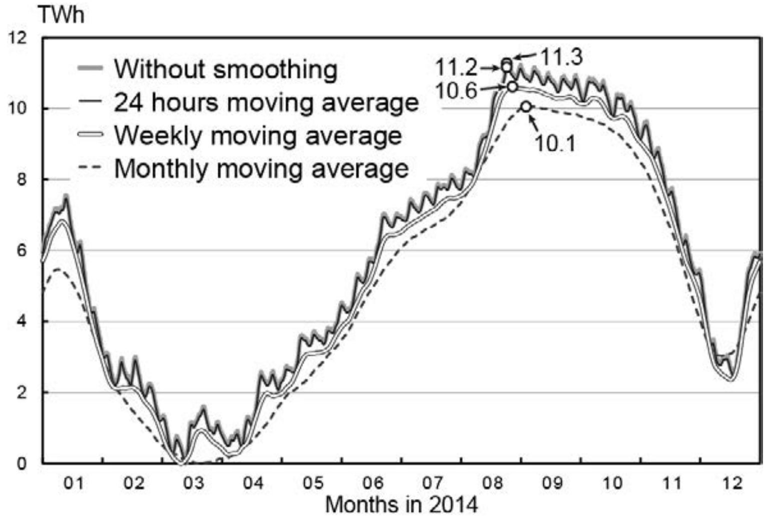
Unfortunately, however, closer inspection of Figure 7 reveals that the storage requirement results from long-term seasonal fluctuations rather than short-term frequencies of a few hours or days. It would be necessary to store energy from August to the winter months through March, in other words for nearly 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 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

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

of 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.

Figure 8: Absorbing high frequencies with demand management



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 to 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. This is still an enormous quantity compared to the 35 pumped-storage plants that exist in Germany.

5. 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.[10] Arguably, the most promising alternative is methane, which is basically the same as natural gas. After all, Germany has a methane storage capacity that covers 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

[10] See Sterner (2010) and Fuchs et al. (2012) for excellent overviews of the available alternatives.

smooth the normal volatility in German power demand and supply.[11] 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 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.[12] 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 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 Carnot’s Theorem, which is based on the second main theorem of thermodynamics, any conversion of heat into motion energy or electric

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[11] Bundesministerium für Wirtschaft und Energie (2015). The storage capacity is 24.6 billion m^3 and $1m^3$ is equivalent to 10.848 kWh.

[12] 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 involves huge efficiency losses for physical reasons, quite apart from the technical reasons that add to these losses.[13]

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.[14]

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 be stored as easily 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. One million of 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. As Germany plans to have 1 million electric cars by 2020, presumably similar 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. Thus, arguably, pumped-storage remains the best of the available storage options.

6. Foreign Stores

The pumped-storage plants needed to buffer the volatility of the German net are not only located in Germany, but also in neighbouring countries interconnected via the European power grid. Germany often sells its overproduction to these countries and buys electric power back when there is a supply shortage. While exports net of imports on average accounted for

[13] Thus, for example, a plant that uses vapor at a temperature of $800^{0}C$ and exhausts it at $100^{0}C$ 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.
[14] 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).

6.6% of final German energy consumption in 2014, exports alone stood at 14.5% and imports at 7.9% of overall consumption.[15]

It is often argued that these other countries, and particularly Norway, have enough hydro storage capacity to easily buffer the volatility of the German grid, removing the need for any double structures. Indeed Norway has a huge hydro capacity of 82 TWh, which seems more than enough to cover all of the storage needs calculated above (see Figure 7). Even a six-fold increase in the German wind and solar power, which would bring the percentage of wind and solar power to nearly a hundred percent of Germany's 2014 electricity demand, would result in a required storage volume of "only" 42.76 TWh (39,699 PSP), which is far lower than the actual Norwegian storage volume. Thus the only problem seems to be the currently insufficient interconnector capacity in terms of high-voltage submarine cables, but this problem could easily be solved.

However, this argument overlooks that Norway would not only need the capacity to store energy coming from Norwegian rivers but also from German wind and solar power plants. Under the conditions of the year 2014, it would be necessary to import from Germany and store the 11.29 TWh shown by the peak of the solid combined-storage curve in Figure 7. To this end, Norway would need 10,478 pumped-storage lakes of the German variety. In fact, however, Norway has only very few pumped-storage facilities, which are largely used to prevent upper lakes from drying out for ecological reasons rather than power production.

A solution to all of these problems would be to build more pumped-storage lakes in Europe, and in Norway in particular. This, however, is less trivial than it sounds. In many cases geological conditions do not lend themselves to building or activating a second lake from which the water could be pumped back. Moreover, the need to store the water coming in from rivers often excludes the possibility of storing German energy too. In a number of cases, hydro power lakes empty into the fjords. The alternative of pumping sea water to freshwater lakes or newly built sea-water basins on land involves high ecological risks and is therefore not seen as a viable option in Europe.[16]

Nevertheless, Norway does offer substantial potential for building pumped-storage facilities. According to the EU-financed ESTORAGE project, which screened the geological possibilities in the EU 15 plus Norway and Switzerland, another 2.291 TWh of pumped-storage capacity could potentially be built in Western Europe, of which a good half could be

[15] Arbeitsgemeinschaft Energiebilanzen e. V., Energiebilanz 2014.
[16] There is, however, a sea-water pumped-storage plant in Okinawa, Japan. See Hiratsuka, Arai and Yoshimura (1993).

made available in Southern Norway alone.[17] According to the EU Commission, the additional capacity would be *more* than seven times the current capacity, so it follows that the current pumped-storage capacity in western Europe, including Norway and Switzerland, is about 300 GWh (definitely less than 327 GWh). [18] The production programme considered realizable by the ESTORAGE study would increase the overall western European pumped-storage capacity eightfold to a maximum of 2.618 TWh. Even this capacity, however, would be small compared to the 11.29 TWh that Germany would need to stabilize its net via storage devices under its 2014 technological conditions.

7. 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 already present, methanation plays no role, and pumped-storage devices have a miniscule capacity relative to what would be needed. The answer is that Germany has to use its existing fossil fuel plants to cushion the shocks resulting from inserting wind and solar energy into the grid. In fact, the difference between the consumption and production curves in Figure 6 is being offset by conventional production in Germany and international trade, primarily with Austria. 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 peaks are exported to other countries. When there is no wind and sunshine, by contrast, conventional plants 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.

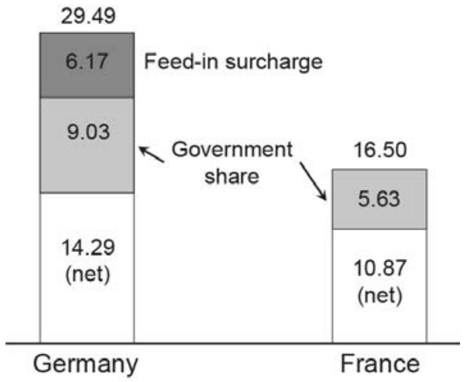
To some extent even lignite plants and nuclear power plants are used to buffer volatility. In the case of lignite plants, a couple of days are required for a cautious shut down and re-start to avoid damage to the steam boilers. Moreover, while nuclear plants require days

[17] KEM (2015), EU project.
[18] See European Commission (2016).

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.[19]

While the German buffering strategy has thus far prevented black-outs in the grid, it is extremely expensive and inefficient, as it involves double structures with double costs. Firstly, it has undermined the profitability of conventional power plants, which are often forced to produce below capacity, threatening the existence of huge power companies like Eon or RWE; and secondly, it has made electricity 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.

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.

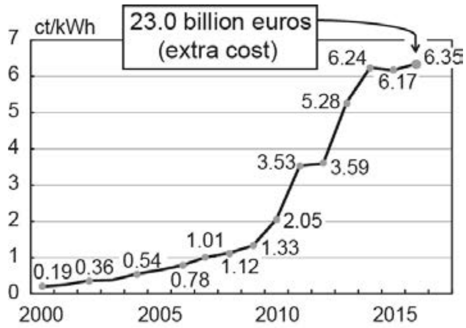
The high cost of electricity in Germany partly results from the differing wholesale prices of electric power in Germany and France, and partly from taxes and a feed-in surcharge for green energy. The network companies have to pay the green producers the publicly-administered prices, but when these prices 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.

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

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

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. To put this figure into perspective, this represents about a hundred times the annual budget of government-financed Max-Planck Institute in Greifswald which run an experimental nuclear fusion reactor, the Stellerator.

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.

Although it remains doubtful whether the German solution has been able to reduce European CO_2 emissions, given that these emissions are already defined by the EU's cap & trade system, it is clear that the German double-structure strategy is uneconomical from a national point of view, as long as the *marginal* cost of producing electricity from fossil fuels falls short of 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.[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 meet its goals, the average cost of wind and solar energy would have to fall by more than two thirds.

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

8. The Double-Structure-cum-Storage Strategy

While the German double-structure strategy is working for the time being, it faces obvious limits when the production peaks overshoot consumption, given that conventional plants including hydroelectric power stations 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 2014, German power demand exceeded wind and solar power production.[21] However, in March, April and August there were obviously times when the upward production peaks came close to the downward demand peaks.

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. 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.[22]

The surplus power was subsequently often unloaded to the grids of other EU countries at negative prices. The German government extols the country's power exports due to the increase in green electricity on its website,[23] but it fails 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 removal, because waste is what the green surplus power had become.[24]

Other European countries like Poland or the Czech Republic complained about the sale of northern German wind power to Austria, as the power flow was finding its path through their nets, overloading them and bringing them close to a black out. They reacted by installing phase shifter transformers at the borders to block the transportation of German power. 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 caused political irritations between Austria and Germany, prompting the European regulation agency ACER to propose a

[21] In higher resolution data, however, overshooting spikes may have occurred.
[22] See Götz, Henkel, Lenck and Lenz (2014).
[23] See Deutsche Bundesregierung (2014).
[24] A more optimistic view on interregional diversification and buffering possibilities is painted for the US in a paper by Heal (2016).

separation of the previously joint power markets.[25] Even Bavaria has resisted building power lines to northern Germany, so as to avoid being forced to import the power spikes and to keep its gas and coal power plants profitable.

German power grid companies, which are legally forced to absorb the green electricity when it comes, have reacted to the negative prices and the bottlenecks by asking wind turbine owners to stop producing, paying them up to 90% of the administered feed-in tariffs for their foregone production. 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 for being asked to stop their generators and not produce electric power, although enough wind was available.[26] Such difficulties will increase if Germany continues its path 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 in Germany. As mentioned above, this strategy reaches its natural limits if production peaks exceed power consumption because conventional plants cannot easily be converted to energy stores that absorb rather than produce electric power. If higher shares of wind and solar energy are to be fed into the grid, the surplus production will either have to be wasted, buffered by stores or absorbed by other countries curtailing their production. The following discussion abstains from exploring the latter possibility, as the growing resistance apparent in negative energy prices suggests that Germany should find strategies that would avoid using neighbouring grids as shock absorbers other than by explicitly buying their storage services. Moreover, if the German strategy is to serve as an example for the rest of Europe, that strategy cannot involve Germany simply unloading its volatility to other countries' grids, given that seasonal weather and consumption patterns are very similar throughout western Europe. Thus the analysis focuses on a double-structure-cum-storage strategy alone: Germany buffers as much of the volatility as possible by adjusting the production of conventional plants inversely to wind and solar power and shifts the overshooting production spikes by way of internal or external storage to periods of excess demand.

Figure 11 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

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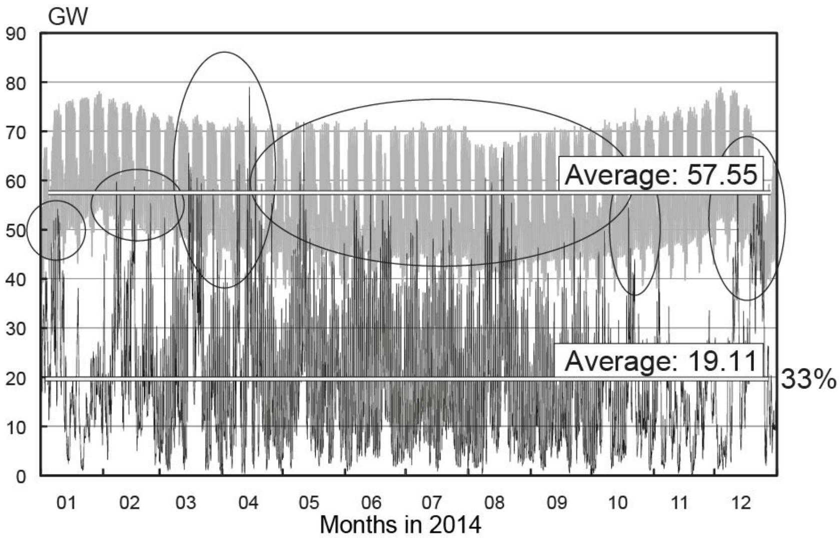
[25]See "Stromstreit an der deutsch-österreichischen Grenze", *Frankfurter Allgemeine Zeitung* No. 253, 29 October 2016, p. 22, or http://www.faz.net/aktuell/wirtschaft/energiepolitik/stromhandel-an-grenze-zu-oesterreich-eingeschraenkt-14502066.html.
[26] See Bundesnetzagentur (2016).

seasonal volatility of demand and supply, it does not seem to be an outlier.[27] If anything, global warming looks set to make the weather more volatile and result in more pessimistic conclusions than those reported here. 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.

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



As shown in the figure, some of the production spikes would overshoot consumption demand if wind and solar supply were to double. 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 other countries. Let us remember that the 33% output share reached by doubling wind and solar power would generate enough additional energy for Germany to be able 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. Nevertheless, the calculations as such are independent of the question of which kinds of plants are being replaced.

The volume of the overshooting spikes shown in Figure 11 is tiny, only 0.4% of the wind and solar supply. Thus the question of whether or not the overshooting production is stored or wasted does not seem overly important if wind and solar power is merely doubled,

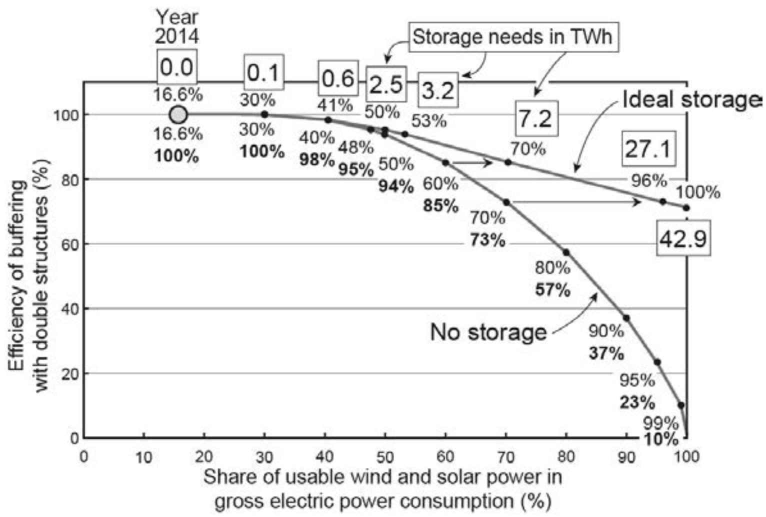
[27] Analyses of previous years already conducted by the author did not generate qualitatively different results as the year 2014 was not characterised by unusual weather conditions.

and not much storage space would be required to avoid the losses. The situation changes progressively, however, if wind and solar energy is expanded further.

Figure 12 reports the results of alternative calculations with higher shares of wind-solar power. It 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 one without and the right one with (ideal) 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 curve without storage. Here all buffering comes from adjusting conventional production, and overshooting spikes are wasted. The curve shows that the efficiency of a pure double-structure strategy stays close to 100% for wind-solar market shares up to about one third, but dwindles progressively towards zero as the market share approaches 100%. 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 – if steadily rising efficiency losses are to be avoided. While 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 90% with an efficiency of just 37%, implying that two thirds of the energy would be lost, if no stores were available.

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 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. 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 right-hand curve shows the market share resulting from saving the overshooting spikes with ideal stores to avoid any waste and making 100% of wind and solar power usable. The stores increase the market share of wind and solar power and shift the market-share curve to the right.

The question is how large the necessary storage volume would be. The small boxes above the curves show the respective storage space required in TWh. The required storage volume is calculated on the assumption that all surplus power is channelled into stores, and subsequently released as quickly as possible by satisfying excess demand when it occurs, i.e. by filling the gap between consumption and wind-solar supply (the excess load) and thus displacing the corresponding amount of conventional power. Emptying the stores as quickly as possible when solar and wind power is insufficient to meet all demand is useful to gain free storage space for new overshooting spikes and to minimize the required storage space. The calculations assume that the storage volume at the beginning of the year is the same as the volume at the end of the year, and that the store is empty for at least one hour per year. Thus, it is assumed that as much buffering as possible is done by reducing conventional production – the double structure strategy – and as little buffering as possible by storage.[28]

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. 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.

To help interpret the graph, let us suppose, for example, that a market share for wind and solar power of 50% is to be achieved without storage. In this case 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 2.5 TWh.[29] 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, it still is about 66 times the storage volume (0.038 TWh) that Germany's 35 pumped-storage plants currently provide.

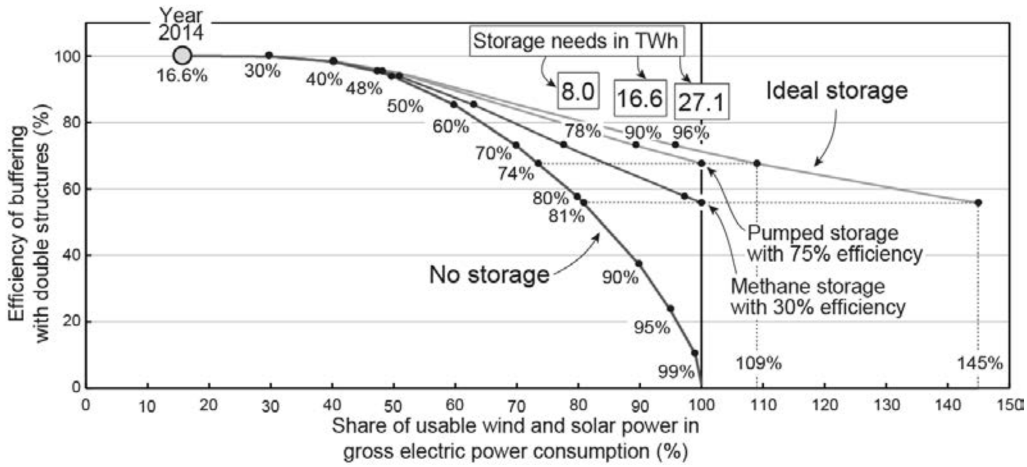
While ideal, frictionless stores have been assumed in this paper thus far, Figure 13 extends the analysis to more realistic assumptions about energy losses resulting from the storage detour. Pumped stores with an efficiency of 75% (81% input, 92.6 output) and methane stores with an efficiency of 30% (60% input, 50% output) are assumed, along the lines discussed above in Section 5. This means that storage shifts the market-share curve less to the right than in the case of ideal storage. The figure illustrates this numerically for a

[28] 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.

[29] 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 storage volume of 3.5 TWh, which is substantially higher than with the new storage strategy (2.5 TWh). See Sinn (2016, July version of this paper).

particular set of wind and solar plants that in the case of a double-structure-only strategy would result in a market share of 70%. If supported by methane storage this market share could be increased to 78%, and if pumped stores were available, the market share would even be 90%, while the theoretical market share of 96% resulting from ideal storage (see also Figure 12) could not be reached. As is indicated by the small boxes above the curves, the required methane-storage capacity would be 8.0 TWh, and the required pumped-storage capacity would be 16.6 TWh. The latter is substantially less than the theoretical storage volume of 27.1 TWh in the case of frictionless stores, but still a multiple of what could possibly be built in western Europe according to the ESTORAGE study.

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



More details of the calculations underlying Figures 12 and 13 are given in Table 1. Column 1 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. Columns 2 to 4 refer to the case of ideal storage, pumped storage and methane storage, respectively. Their sub-columns show the respective i) market share, ii) degree of efficiency with storage and iii) required storage capacity. Each line in the table shows one particular multiple of the wind and solar devices installed in Germany in 2014.

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

(1) No storage		(2) Ideal storage			(3) Pumped storage[1)]			(4) 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%	0.0	30.0%	99.9%	0.0
40.0%	98.3%	40.7%	100.0%	0.6	40.5%	99.6%	0.4	40.2%	98.8%	0.2
47.6%	95.2%	**50.0%**	**100.0%**	**2.5**	49.4%	98.8%	2.0	48.3%	96.7%	1.4
48.1%	95.0%	50.6%	100.0%	2.6	**50.0%**	**98.7%**	**2.1**	48.9%	96.5%	1.5
49.1%	94.4%	52.1%	100.0%	2.9	51.3%	98.6%	2.4	**50.0%**	**96.1%**	**1.7**
50.0%	**93.8%**	53.3%	100.0%	3.2	**52.5%**	**98.5%**	**2.6**	51.0%	95.7%	1.9
60.0%	85.2%	70.4%	100.0%	7.2	67.8%	96.3%	5.8	63.1%	89.6%	4.3
70.0%	**72.9%**	**96.0%**	**100.0%**	**27.1**	**89.5%**	**93.2%**	**16.6**	**77.8%**	**81.0%**	**8.0**
71.2%	71.2%	100.0%	100.0%	42.9	92.8%	92.8%	19.0	79.8%	79.8%	9.2
73.6%	67.7%	**108.8%**	91.9%	-	**100.0%**	91.9%	**42.0**	84.2%	77.4%	13.9
80.0%	57.4%	139.3%	71.8%	-	-	-	-	97.8%	70.2%	39.3
80.9%	55.9%	**144.7%**	69.1%	-	-	-	-	**100.0%**	69.1%	**55.9**

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.

Let us consider, for example, the case of appliances that without stores would result in a market share of 70%. In this case it would be possible to increase the overall efficiency from 72.9% (no storage) to 93.2% at a market share of 89.5% with pumped-storage plants, and to 81.0 % at a market share of 77.8% with methane storage.

The table shows that a market share of 100% reached by combining double-structure buffering with methane storage requires a wind and solar production equal to 144.7% of demand (Column 2, last item in first sub-column), while a storage capacity of 55.9 TWh would be necessary (Column 4, last item in last sub-column). Similarly, if a combination of double structures with pumped-storage is to generate a wind-solar market share of 100%, wind and solar production needs to be 108.8% of demand with a storage capacity of 42.0 TWh. The respective necessary excess production values can also be read from the ideal-storage curve in the right-hand region of Figure 13.

Let us now consider again the less ambitious plan to realise a wind and solar market share of just 50%, which would, as mentioned above, require a storage volume of 2.5 TWh if frictionless stores were available. In the more realistic case with frictions, the required storage volume for this market share would shrink to 1.7 TWh and 2.1 TWh with methane and pumped stores respectively. This would involve installing more wind and solar plants to compensate for the frictions, given that a 50% market share is to be achieved. While the required methane-storage volume would not face binding constraints, the required pumped-storage of 2.1 TWh is about 7 times western Europe's current pumped-storage capacity (less than 327 GWh) and 81% of the entire storage capacity that according to the EU's ESTORAGE project could be realized in western Europe, including Switzerland and Norway (2.6 TWh), after an eight-fold increase in western Europe's pumped-storage capacity, as was mentioned in Section 6.[30]

Let us suppose, finally, that the entire future pumped-storage capacity that the ESTORAGE project finds realisable in western Europe, including Norway and Switzerland, were to be used to buffer Germany's excess production alone, while a maximum of buffering is achieved by German double-structures. In this case, a wind-solar market share of 52.5% could be reached in Germany.

9. Concluding Remarks

While mankind has almost no alternative to replacing fossil fuels with energy sources that do not contribute to global warming, this paper has studied the difficulties resulting from Germany's attempt to solve the problem with solar and wind energy. The main barrier is the enormous volatility of this type of green energy. 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 ideal pumped-storage plants of the average German size, whereas Germany currently only has 35 such plants. Any bid to also smooth Germany's extremely volatile power consumption would increase the storage capacity needed to about 11 TWh or 10,500 ideal pumped-storage plants, even although much wind and solar power happens to be available in seasons with large demand.

Another buffering strategy is active demand management through peak load pricing. However, as Figure 8 showed, this strategy would not significantly reduce the storage requirement. Smoothing short-term variations during a day, a week or a month would reduce the needed storage volume 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.

[30] See again KEM (2015) and European Commission (2016).

Thus, buffering the volatility from wind and solar energy with double structures, i.e. basically maintaining the conventional 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 green plants, rather than substitutes for them 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, or if other countries' conventional plants take over this function. From an environmental perspective, Germany would be well-advised to at least convert its fossil fuel plants to gas power plants, as their CO_2 emissions only account for around half of the emissions generated by coal-fired plants. However, Germany has not yet introduced a pricing scheme that would compensate the owners of traditional power plants, including gas-powered plants, for offering such flexible services. Under the current pricing regime, wind and solar power reduce the profitability of conventional plants and place them at risk of being shut down, even although these conventional plants are indispensable complements to green energy. [31]

Regardless of this economic difficulty, the German strategy of buffering the volatility with double structures will enter uncharted waters when the wind and solar production spikes begin to overshoot demand. It follows from Figures 1, 11 and 12 that this will be the case when this type of green energy stands at about one third of aggregate electric power production. This happens to be the point at which Germany could, as planned, abandon all of its remaining nuclear plants. 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 peaks comprise an increasing fraction of output, which will either have to be wasted or smoothened through stores. Note, however, that the same problems would arise at higher market shares for wind and solar energy if fossil instead of nuclear plants were abandoned.

[31] Bavaria has partially 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 degraded it to a stop-gap plant and deprived it of its profitability.

As shown, reaching an overall 50% share of wind and solar energy in the entire production of electric power would require 2.5 TWh of ideal storage capacity, or 2.1 TWh of pumped-storage plants with the usual technological frictions. The required capacity is 56 times the capacity of pumped stores currently available in Germany and 81% of the entire pumped-storage capacity that, according to the EU's ESTORAGE project, could be realised in western Europe including Switzerland and Norway. Exploiting the entire future pumped-storage capacity of western Europe for Germany alone would bring the German market share of wind and solar power to 52.5%. Moving beyond this point is not possible without wasting increasing shares of the produced energy or using other countries' conventional plants as buffers and reducing their degree of capacity utilization.

A further option might be 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 that the storage requirement 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 its advantages are not that obvious, especially if the difficulties in handling and transporting hydrogen are taken into account.

In view of all these difficulties, it is imperative that the world community and other EU countries carefully observe the outcome of the German experiment before mimicking it.

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