

Controlling volatility of wind-solar power

Hans Lustfeld

Peter Grünberg Institut (PGI-1), Forschungszentrum Jülich 52425 Jülich, Germany

Abstract

The main advantage of wind and solar power plants is the power production free of CO_2 . Their main disadvantage is the volatility of the generated power. According to the estimates of H.-W. Sinn[1], suppressing this volatility requires pumped-storage plants with a huge capacity, several orders of magnitude larger than the present available capacity in Germany[2]. Sinn concluded that wind-solar power can be used only together with conventional power plants as backups. However, based on German power data[3] of 2019 we show that the required storage capacity can significantly be reduced, provided i) a surplus of wind-solar power plants is supplied, ii) smart meters are installed, iii) partly a different kind of wind turbines and solar panels are used in Germany. Our calculations suggest that all the electric energy, presently produced in Germany, can be obtained from wind-solar power alone. And our results let us predict that wind-solar power can be used to produce in addition the energy for transportation, warm water, space heating and in part for process heating, meaning an increase of the present electric energy production by a factor of about 5[1]. Of course, to put such a prediction on firm ground the present calculations have to be confirmed for a period of many years. And it should be kept in mind, that in any case a huge number of wind turbines and solar panels is required.

Keywords: volatility, storage, offshore, weak-wind turbine, low-light solar cell, smart meters

1. Introduction

Apart from nuclear power and hydropower (power from biomass and waste could be mentioned, too), the conventional electric power production by gas and fossil fuel power stations generates CO_2 as a byproduct. Nuclear power plants do not have this problem, but they have other disadvantages, in particular production of radioactive waste. All these problems do not appear when electric power is produced by solar panels and wind turbines alone. Nevertheless, wind-solar power has serious disadvantages too, the most serious one being the volatile energy production: Weather conditions change rapidly and as a consequence

Email address: h.lustfeld@fz-juelich.de (Hans Lustfeld)

energy production of wind-solar power fluctuates considerably. How serious the consequences are, depends on two factors: i) the strength of the volatility, ii) the volatility that a consumer can tolerate - cf. the key phrase "new thinking"[4].

The problem of volatility is always a consequence of the mismatch between electric power production and electric power consumption. If we just consider passive storage devices, like pumped-storage plants, for example, the strength of volatility can be determined in the following way. We divide the wind-solar energy production P_v and the energy demand P_d into two parts: the average parts P_{va} and P_{da} being constant over the year and the fluctuating parts P_{vf} and P_{df} . The power P_{sf} streaming into and out of storage devices has a fluctuation part only since the devices are passive. The average of each fluctuating part is zero. Therefore we get the simple equations

$$P_{va} = P_{da} \quad (1)$$

and therefore,

$$P_{sf} = P_{vf} - P_{df} \quad (2)$$

Integrating these powers yields the energies

$$\begin{aligned} E_{v(d)}(t) &= E_{va(da)}(t) + E_{vf(df)}(t) \\ E_{va(da)}(t) &= P_{va(da)} \cdot t \\ E_{vf(df)}(t) &= \int_0^t P_{vf(df)} dt \\ E_{sf} &= E_{vf} - E_{df} \end{aligned} \quad (3)$$

The required storage E_{sfmax} is obtained from the expression

$$E_{sfmax} = \max_t \{E_{sf}(t)\} - \min_t \{E_{sf}(t)\} \quad (4)$$

In order to obtain these functions for 2019, we have used the data of ref[3] which contain power measurements every 15 minutes [in MW] for electric load and the volatile power, consisting of: offshore and onshore windpower as well as solar power. The result is obtained directly for the demand (load): $P_{da} = 56.4\text{GW}$ and the fluctuation part E_{df} is plotted in Fig.1. The correct values for P_{va} and P_{vf} require a moment of consideration. The measurement data lead to the value $\hat{P}_{va} = 18.9\text{GW}$.

Since we intend to satisfy the average electric energy demand by wind-solar power alone, we need an average electric power production of at least $P_{va} = P_{da} = 56.4\text{GW}$ as well. To manage this problem, we assume that the distribution of solar cells and wind turbines is already at its optimum in Germany. In that case we can easily estimate the situation where all average electric energy is delivered by wind-solar power: We just have to multiply the average wind-solar power and its fluctuation by a scaling factor[1]. Clearly the distribution of wind-solar power is not at its optimum in reality. Therefore, the scaling is an approximation. However, understanding the trends is the aim of this paper and for that purpose the scaling will be a sufficiently good approximation. As the distribution becomes increasingly optimized, such an approximation will

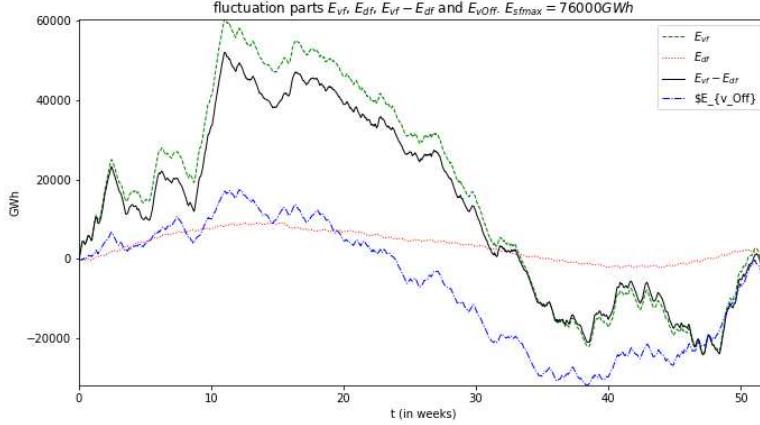


Figure 1: Fluctuation parts and storage: (Green) dashed line: Fluctuating part E_{vf} of (scaled) volatile energy E_v . (Red) dotted line: Fluctuation part E_{df} of energy demand E_d . (Black) solid line: (Scaled) fluctuating part E_{vf} of wind-solar energy minus fluctuating part E_{df} of demand E_d . From the difference between max and min the required storage can be read off. Note the dominance of E_{vf} . For comparison the fluctuation part E_{vOff} of the (scaled) offshore energy E_{vOff} is shown. Here the scaling factor is 56.4/2.76

steadily improve. Now taking as natural scaling factor 56.4/18.9 for wind-solar power we get

$$\begin{aligned} P_{va} &= \hat{P}_{va} \cdot \frac{56.4}{18.9} = P_{da} \\ P_{vf} &= \hat{P}_{vf} \cdot \frac{56.4}{18.9} \end{aligned} \quad (5)$$

where \hat{P}_{va} and \hat{P}_{vf} are obtained from the measurement data. In the same way we get the scaled integrated quantities E_v, E_{va} and E_{vf} after scaling the original mathematical expressions with the same factor. Together with the scaling factor 56.4/18.9 those expressions will be used throughout this paper. Of course, wind-solar and demand data differ from year to year, but, considered over the year 2019, the typical properties should be similar enough to reveal the relevant trends. For a detailed technical analysis, the observation period of one year does, of course, not suffice. Instead, observation periods over many years are necessary. This is possible, but beyond the scope of the present paper.

As a first application we calculate the storage capacity necessary to fulfill eq.[2] and we find: the required electric storage removing volatility is 75.9TWh, cf. eq.4 and Fig.1.

This result proves that volatility is a serious problem. Indeed volatility led Sinn to the conclusion that energy production resting essentially on wind-solar power alone will take us into an economic nirvana[5]. One could argue that even a total storage capacity of about 84TWh[1], [2] is in principle feasible by transforming the huge Norwegian hydro dams into pumped-storage plants.

However, two facts are obvious: i) The present electric power production has to be multiplied by a factor of about 5 [1], if all transportation, warm water, space heating and a considerable percentage of process heating are switched to electric power as well. With the configuration presented here so far, this is impossible. ii) Even if we do not consider transportation, warm water, space heating, and process heating, the pump storage capacity requirements would be so enormous that an export of this wind-solar scheme to many other nations would be out of the question - a bitter disadvantage when Germany wants to be a forerunner.

How can we successfully proceed? Of course we need a kind of active buffering. Sinn [1] suggests various combinations between wind-solar power and conventional power plants. This works for the present needs but eliminates the advantages of using wind-solar power alone. Furthermore, this scheme becomes questionable if the needs of electric power are five times greater than now. And that will happen if energy production of Germany will be switched to electric power generation as far as possible.

In this paper we discard such schemes. Instead we suggest a combination of three methods: First, creating a surplus of wind-solar power. Second, applying smart meters[4]. Both methods are described in section II. We show that through these methods the storage capacity requirements are reduced by a factor of about 50 or even become marginal. Third, applying new criteria for optimizing the efficiency of wind turbines, solar cells and their distribution across the country. We show in section III that through these additional methods the smart meters need distinctively less flexibility. We think that these results give us the justification for extrapolating to the case where in addition to the present electrical energy production all energy for the total transport, warm water, space heating and and a considerable percentage of process heating is exclusively obtained from wind-solar power. This is discussed in section IV. Our conclusions are presented at the end of the paper.

2. Surplus of wind-solar power and smart meters

In this section we discuss the situation, in which the generation of electric power is taken over by wind-solar power alone.

In contrast to simple passive buffers like pumped-storage plants with all their capacity limitations active buffers like power plants can satisfy the demand necessary for guaranteeing a safe power delivery. To avoid CO_2 production we choose as active buffers wind-solar power itself. Assuming[1] as above an already optimum distribution of wind-solar power devices across the nation, the surplus of wind-solar power can be expressed again by a scaling factor α , the strength α , and we get for the wind-solar energy

$$E_v(t) \longrightarrow (1 + \alpha)E_v(t), \alpha = \text{const}$$

The price to be paid for this scheme is a reduced efficiency. This is all the more the case since at times of low wind-solar power the surplus of wind-solar power is reduced as well enforcing a larger α value than expected from the average

gain in power. To keep α within reasonable limits we need the concept[6] and on a large scale the application[7] of smart meters[4]. Such devices control the electrical consumption very effectively by setting higher consumption prices if less power is available and lower prices if there is a surplus of power. Thus smart meters act like passive buffering devices by moving the peaks of electric consumption to the peaks of wind-solar power. We note in passing that moving electric consumption on an hourly basis or less has the same effect as smoothing, cf. ref. [1], section 4.

Of course a detailed simulation of smart meters is intricate. However, we think that the following simulation of smart meters reflects the principle effects satisfactorily: $E_d(t)$ is the energy of electric consumption as function of time. Now, if wind-solar production is not sufficient, it produces energy corresponding to a demand $E_d(t') < E_d(t)$. The smart meters have now the task, by increasing prices for $1kWh$ to enforce a reduced demand, namely $E_d(t')$. Clearly that is always possible - due to exorbitant prices, if necessary. But to avoid such uneconomic incidents we introduce the delay time $\tau \geq 0$ and require $t' > t - \tau$. The analogous happens for a surplus of wind-solar power: If there is an excess production of electric energy, corresponding to $E_d(t') > E_d(t)$, smart meters charge low prices and E_d is again not that of time t but that of t' and $t' < t + \tau$. This means the strict requirement $t' = t$ is replaced by

$$E_d(t - \tau) < E_d(t') < E_d(t + \tau), |t' - t| \leq \tau \quad (6)$$

As is the case in the applications of real smart meters, the electric power consumption becomes more flexible in this simulation. The produced energy till time t need not be $E_d(t)$ exactly but staying in the interval of eq.(6) suffices. This flexibility saves storage capacity as can be seen from an extreme (hypothetical) case: If τ becomes sufficiently big the required storage capacity approaches zero. Of course such large values of τ are unrealistic. However, values of hours or even days can be acceptable. We assume that a limit $\tau \leq 1\text{day}$ is a very reasonable one. And note, this simulation of smart meters fulfills the criterion that - as in real smart meters - consumption of energy is only moved, no energy is generated or lost.

To avoid large τ values, finite α -values and possibly electric buffering devices are still needed. We find out the relation between delay time τ , capacity E_{sfmax} , and strength α in the following manner:

We fix α and τ , proceed in time steps $\Delta t = 15\text{min}$ and define $E_d(t') = \check{E}_d$. At the beginning we set $\check{E}_d = 0$ and $E_{sf} = 0$. Now at time $t + \Delta t$ we get

$$\delta E_v = (1 + \alpha) P_v(t) \cdot \Delta t$$

Now three cases have to be distinguished (we set $s = t + \Delta t$):

- i) $E_d(s - \tau) \leq \check{E}_d + \delta E_v \leq E_d(s + \tau)$, then $\check{E}_d \rightarrow \check{E}_d + \delta E_v$.
- ii) $\check{E}_d + \delta E_v > E_d(s + \tau)$, then $\check{E}_d \rightarrow E_d(s + \tau)$ and $E_{sf} \rightarrow E_{sf} + \check{E}_d + \delta E_v - E_d(s + \tau)$
- iii) $\check{E}_d + \delta E_v < E_d(s - \tau)$, then $\check{E}_d \rightarrow E_d(s - \tau)$ and $E_{sf} \rightarrow E_{sf} + \check{E}_d + \delta E_v - E_d(s - \tau)$

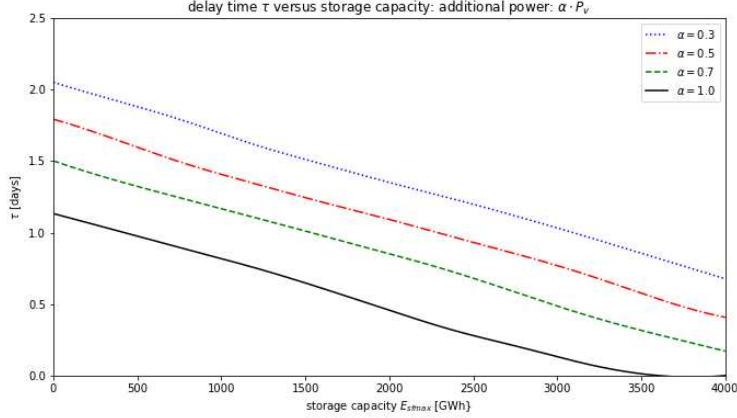


Figure 2: Delay time τ [days] versus storage capacity E_{sfmax} [GWh] for various values of the strength α . The curves demonstrate that a decrease of the storage capacity can indeed be compensated by an increase of α . E.g. $\tau = 1$ day can be obtained by setting $\alpha = 0.3$ and storage capacity of 3100 GWh or $\alpha = 0.5$ and storage capacity of 2400 GWh or $\alpha = 0.7$ and storage capacity of 1500 GWh or $\alpha = 1.0$ and storage capacity of 400 GWh.

Furthermore, to save storage, we enforce $E_{sf} \leq 0$ by replacing a positive E_{sf} with zero. Thus a positive E_{sf} becomes a kind of 'wasted' energy that has to be removed somehow (see below). At the end of the calculation E_{sfmax} is given by

$$E_{sfmax} = \max_t \{-E_{sf}(t)\}$$

Repeating this procedure for various τ values we get the function $E_{sfmax}(\tau, \alpha)$ and from that function the inverse function $\tau(E_{sfmax}, \alpha)$.

Results of our calculations are shown in Fig.2. We have plotted $\tau(E_{sfmax}, \alpha)$ for various fixed α values. The results contain the important conclusion that storage capacity can be replaced by a surplus of wind-solar power. This phenomenon opens a wide field of possibilities: If storage capacity does not represent a problem $\alpha = 0.3$ might be sufficient. On the other hand storage capacity becomes rather uncritical for $\alpha \geq 0.5$. And for $\alpha = 1$ the storage capacity is no longer a problem.

The arising 'wasted' energy need not be small at all. In fact, if all possible energy is generated the average power amounts to $(1+\alpha) \cdot 56.4\text{GW}$ and thus the average 'wasted' power to $\alpha \cdot 56.4\text{GW}$. To get rid of it directly is one possibility. This can easily be achieved by reducing the wind-solar power, as soon as 'wasted' energy begins to build up. The advantage of this procedure would be a strain imposed on the electricity network that would not essentially be higher than for $\alpha = 0$.

An alternative would be exploiting this 'wasted' power for processes, e.g. for electrolytic and chemical processes. However one has to keep in mind that the surplus power is really extremely volatile as can be seen from Fig.3 for $\alpha = 0.5$.

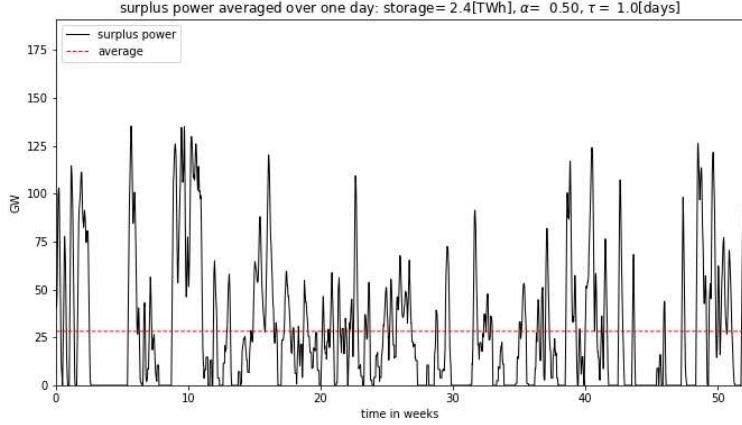


Figure 3: 'Wasted' power for storage capacity 2400GWh , $\alpha = 0.5$, $\tau = 1.0$ days. This power is generated, if the surplus wind-solar devices work all the time with maximum power available. (Black) solid line: 'Wasted' power averaged over $24h$. (Red) dashed line: 'Wasted' power averaged over one year. The averaged value is $\alpha \cdot 56.4\text{GW}$.

Apart from high peaks there are - more important - periods, even weeks, where no 'wasted' power is available.

The absolute costs per kWh depend on assumptions, of how prices will develop in the future and which indirect costs have to be included in the calculation and which not. In fact, the estimates fluctuate strongly[1][8][9]. However, the relative increase of running costs per kWh due to the 'wasted' power can be assessed: For a small contribution of wind-solar power - so small, that peaks do not overshoot consumption - suppose running costs in the average to be $ws_{small}[\text{€}/\text{kWh}]$. However, we do not deal with a small contribution. Instead an average demand of 56.4GW has to be satisfied. Applying the surplus power approach fulfilling this demand requires an average production of $(1 + \alpha) \cdot 56.4\text{GW}$. Therefore, the increase of the running costs is $ws_{small} \rightarrow ws_{small} \cdot (1 + \alpha)$ and the relative increase is given by α .

3. Low energy production and offshore wind turbines

At first sight it may seem obvious that wind-solar power should have its nominal power at high winds, at high sun radiation and moreover in regions with high winds and high sun-radiation, respectively. But the surplus wind-solar power becomes important if the wind-solar power production is weak and therefore weak-wind turbines and solar cells with good low-light performance will be essential for good additional power production. Weak-wind turbines having blades enlarged by a factor[10] $\sqrt{\beta}$, greater height[11] and thus higher wind speed enlarged by a factor[12] $(\gamma)^{1/3}$, provide an increase of power generation by

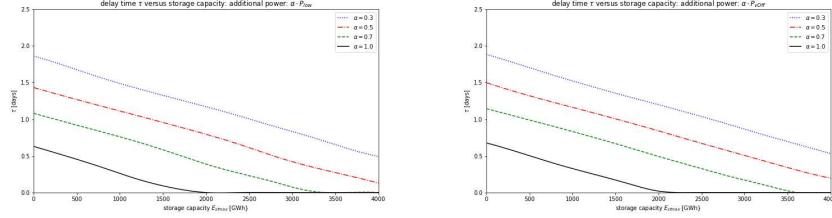


Figure 4: Delay time τ [days] versus storage capacity E_{sfmax} [GWh] for various values of the strength α . Left: The surplus power αP_{low} has enhanced performance at low wind and low radiation, cf. eq.[7] leading to distinctively shorter delay times τ . Right: The surplus power αP_{Off} is delivered by offshore wind turbines. Their averaged contribution to the electric power generation is still small, only 2.8GW in 2019. However, a continuous expansion is intended, therefore we have scaled the present offshore power generation by a factor of 56.4/2.8. So for $\alpha = 0.5$ the required offshore power has to exceed the value of 2019 by a factor of 10. According to our calculations such an expansion would lead to promising results: Again distinctively shorter delay times τ .

a factor of $\beta \cdot \gamma$. We choose $\beta \cdot \gamma = 2$. This doubles the power production in the low-wind regime, $P_l = 2 \cdot P$. In the high wind regime, however, the power production saturates since these turbines have a reduced nominal power[12] P_{nom} . This justifies the ansatz

$$P_l(t) = P_{nom} \cdot \tanh(\beta \cdot \gamma \cdot P(t)/P_{nom}), \beta \cdot \gamma = 2$$

Weak-light performance of solar cells[13] depends on the material used[14]. Mono-crystalline PV modules[15], multi junction[16] with selected band gaps and in the future the new generations of DSSCs[17][18] may have good weak light performance. And we assume that with good weak light performance the generated power can increase - as for the wind power - by a factor of 2 also in the weak-light regime. (This approximation may be crude but less important as well, since the capacity factor of solar cells is dismal, at least in Germany[19], 10 – 13 %, and therefore the dominant power generation will be that of wind turbines). So we get for the total surplus power (here defined as P_{low}) the ansatz

$$P_{low}(t) = P_{va} \cdot \tanh(2P_v(t)/P_{va}) \quad (7)$$

and

$$\delta E_v = (P_v(t) + \alpha P_{low}(t)) \cdot \Delta t$$

To demonstrate the importance of low energy production, we have selected a low nominal power P_{nom} for P_{low} : $P_{nom} = P_{va}$. And the average wind-solar power is about five times less than the normal nominal power.

The calculations correspond to those of the previous section. Results are presented in Fig. 4. The distinctly better outcome for the delay times τ is obvious in spite of the low nominal power P_{va} of P_{low} . This proves the importance of good performance in weak wind and low light situations.

We found a similar improvement of the results when using offshore wind turbines. We repeated the calculations, only replacing the weak wind power by scaled offshore wind power. With a value of about 20 the scaling factor guaranteeing $P_{va_{off}} = P_{da}$ is rather large since at present the offshore power amounts to 5% of the electric load (average) only, cf. Fig.4..

4. Addition of all possible electric energy in Germany

In the two preceding sections the possibility of applying solar-wind power without excessive use of storage devices has been demonstrated. However, we had only discussed the case of replacing the present electric energy production by wind-solar power. But this amounts to about 20% $\approx 60GW$ [1] over the year, whereas the total energy production amounts to $\approx 280GW$, averaged over the year). 80% consists of energy production for transport on a fossile basis, warm water, space heating and process heating. Converting this energy production into electric power should be possible not completely but to a large extent.

Therefore, the question is inescapable: Can all this electric power be generated by wind-solar power alone. I think a precise answer to this question presumes inspecting all the fluctuation data of wind and radiation across the various parts of Germany over many years. This is possible but beyond the scope of the present paper.

On the other hand, when we look at the required electric storage results for the various examples in the introduction we conclude that compared to the less drastic volatility of electric consumption the volatility of wind-solar power is the dominant part, cf. red dotted curve in Fig.1. But this part can be estimated by simple scaling as in section II, leading to a scale factor of 5. This would mean that the plots in Fig.2 and Fig. 4 remain the same, only the storage values on the horizontal axis had to be multiplied by a factor of 5. Since the storage values are not particularly critical, the effect of scaling would require a shift $\alpha \rightarrow .6$ or $\alpha \rightarrow 1$, which in our view seems to be a tolerable change.

Furthermore we can argue that in spite of its enormous volatility at least part of the 'wasted' power can be used for chemical, in particular electrolytic processes, by which artificial fuel can be produced, e.g. for airplanes. This again would reduce the required wind-solar energy and thus the scaling factor.

It should also be pointed out that in any case the number of required wind turbines is enormous. After conversion into electric power an average power of $\approx 250GW$ [1][1] has to be generated in Germany. Assuming i) a capacity factor of 25% for wind turbines[18]) and ii) a 1/3 contribution of solar power (probably a bit less[20]), a simple calculation leads to a required nominal wind power of 650000MW. This means 430000 {110000} wind turbines of the 1.5MW {6MW} type (height 120m {200m}) are needed to produce the average power. But this is not enough. In our approach this number has to be increased by 60-100% to control volatility.

In view of these large numbers manufacture of wind turbines in mass production should be possible, reducing the cost of wind-solar power.

5. Conclusions

Is it possible to switch all present electric energy production of Germany to wind-solar power? This question has been answered in the negative by Sinn[5]. The main topic of this paper is to show that Sinn's judgement is too pessimistic. When choosing a different ansatz, the results become different: We suggest marginalizing the strong volatility of wind-solar power by i) adding a substantial surplus of wind-solar power ii) installing smart meters[4],[6] iii) selecting different kinds of wind turbines, solar devices and switching to a good deal to offshore wind turbines.

The results of our ansatz are encouraging: The electric storage needed is reduced by more than 90%, even nearly 100% should be possible.

The prize to be paid would be a 50% - 100% surplus of wind-solar power devices compared to the situation in which only the averaged wind-solar power production matches the averaged power consumption.

Our precise data[3] extend over the year 2019, a period sufficient to show that wind-solar power can be promising. Unambiguous results will be confirmed when weather conditions in Germany are carefully analyzed over a period of many years - but this is beyond the scope of the present paper. However, based on the present data, measured every 15 minutes in 2019, our approach avoiding excessive passive storage leads to the following conclusions: First, this approach is applicable to electric energy production in Germany and in other nations also, having no access to huge storage devices. Second, this approach leads to the prediction, that most of the present power demand of Germany could be supplied by wind-solar power alone. Third, this approach does no longer exclude the hope that even if most of the energy production in Germany is switching to electric energy - which means a factor of about 5[1] - , this energy can be delivered by wind-solar power. In this case, however, no matter how we slice it, alone the number of required wind turbines would become tremendous: 430000 [110000] wind turbines of the 1.5MW[6MW] type (height 120m [200m]). Controlling the volatility according to our approach would increase these numbers further by 50–100%. The running costs would rise by a factor $(1+\alpha)$, α being the strength of the additional electric power production, defined in section 2. According to our calculations reasonable values for α are in the range [0.5, 1.0].

References

- [1] Sinn,H.-W., 2017. Buffering volatility: A study on the limits of Germany's energy revolution, European Economic Review 99, 130.
- [2] DNV GL, 2015. Overview of Potential Locations for New Pumped Storage Plants in EU 15, Switzerland and Norway. Seventh Framework Programme, Theme 5. ESTORAGE.
- [3] All consumption and production data of year 2019 obtained from ENTSO-E, the 'European Network of Transmission System Operators for Electricity,

cf.

<https://transparency.entsoe.eu/generation/r2/actualGenerationPerProductionType/show>

- [4] Auer, H., Haas, R., 2016. On integrating large shares of variable renewables into the electricity system, *Energy* 115, 1592–1601 .
- [5] Sinn,H.-W.,2013, Energiewende ins Nichts, christmas lecture 2013 (German),<https://www.youtube.com/watch?v=jm9h0MJ2swo>
- [6] Weranga,K.S.K., Kumarawadu,S., Chandima,D.P.,2013, Smart Metering Design and Applications, Springer, Singapore, 978-981-4451-81-9 (ISBN).
- [7] Krause, S.M.,Börries, S., Bornholdt,S.,2015, Econophysics of adaptive power markets: When a market does not dampen fluctuations but amplifies them, *Phys. Rev. E* 92, 012815 .
- [8] IRENA 2020, Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi. ISBN 978-92-9260-244-4.
- [9] Kost, C., Shammugam, S., Jülich, V., Nguyen, H.-T., Schlegl, T., 2018, STROMGESTEHUNGSKOSTEN ERNEUERBARE ENERGIEN, Fraunhofer ISE March 2018.
- [10] Rao, K., 2019, Wind Energy for Power Generation, Springer, ISBN-13: 9783319751320.
- [11] Knoll, A.,2012, WEA für schwachen Wind halten Onshore-Markt in Schwung, Smarter World, December 03.
- [12] Khalafallah, M. Z., Kandil, H. A., 2018, Wind Turbines for Low-Wind Speed Applications, Scholar'S Press.
- [13] Wirth, H., 2020, Recent Facts about Photovoltaics in Germany, Fraunhofer ISE, June 10.
- [14] Litzenburger, B., Pingel, S., Janke, S., Held, S., Alam, R., 2014, LOW LIGHT PERFORMANCE OF SOLAR CELLS AND MODULES, 29. European Photovoltaic Solar Energy Conference, Amsterdam, the Netherlands, DOI: 10.4229/EUPVSEC20142014-5CV .
- [15] Grunow, P., Lust, S., Sauter, D., Hoffmann, V., Beneking, C., Litzenburger,C., Podlowski, L., 2004, WEAK LIGHT PERFORMANCE AND ANNUAL YIELDS OF PV MODULES AND SYSTEMS AS A RESULT OF THE BASIC PARAMETER SET OF INDUSTRIAL SOLAR CELLS, 19th European Photovoltaic Solar Energy Conference, 7-11 June 2004, Paris, France.
- [16] Dimroth, F., Tibbits, T. N. D., Niemeyer, M., Predan, F., Beutel, P. et.al., 2016, Four-Junction Wafer-Bonded Concentrator Solar Cells, *IEEE Journal of Photovoltaics* 6, 343, DOI: 10.1109/JPHOTOV.2015.2501729.

- [17] Service, R. F., 2018, Solar cells that work in low light could charge devices indoors, *Science, Chemistry, Technology*, DOI: 10.1126/science.aat9682.
- [18] Tian, H., Gardner, J., Edvinsson, T., Patti, P. B., Cong, j., Bo Xu, Abramsson, M., Cappel, U. B., Barea, E. M., 2019, from: *Solar Energy Capture Materials*, ed. Gibson, E. A., PDF eISBN: 978-1-78801-351-2.
- [19] Komusanac, I., Fraile, D., Brindley, G., 2019, eds. Walsh, C., Pineda, I., *Wind energy in Europe in 2018*, WindEurope Feb. 2019.
- [20] Mayraz, N., 2019, Solar power in Germany, Dismal Capacity Factors (10 to 13%), *Energy Central*, October 23.