

An Introduction to Wind Energy

Can „Renewables“ Replace Fossil Fuel and Nuclear Energy in Germany?

By Prof. William Hayden Smith and Dr. Lars Schernikau

Abstract

Electricity can, in principle, power all the energy demands of civilization, provided sufficient electricity can be produced reliably and at an affordable cost.

Here, we detail and summarize the physical mechanisms of wind energy, and pose the question whether the wind resource or the wind plus the solar resource can meet the entire energy demand of Germany as planned under NetZero 2050.

Our back-of-envelope, but physical analysis using only published data, shows that the attainable renewable energy supply is unlikely to match the German future energy demand. The reason is that the total land/sea area required for wind farms and PV parks to power Germany reliably approximates the area of Germany. Grid scale wind-solar energy system creates climatological effects comparable to CO₂, and threatens severe ecological consequences, some of which could be irreversible.

Mining, processing, and fabrication during the energy transition plus the rapid and continual “repowering” of the massive wind farms and PV parks results in materials and commodities demand far exceeding those anticipated. Combined with a decade of decreasing growth of wind power, “Net-Zero” 2050 goals will not be achieved without an enhanced, exponential growth.

The magnitude of the backup for German variable renewable energy is computed and compared with Norway’s total hydroelectric energy storage. The Norwegian hydroelectric storage can meet German electrical demand for less than 6 days, not the required minimum one month. The growth of future electrical energy demand, under “Net-Zero” 2050, necessary to cover all energy demand, eliminates the possibility of a sufficient hydroelectric backup. Other backup options fail, leaving a fundamental unsolved issue.

The conclusion is that the ‘Energiewende’ leaves Germany in thrall to growing energy deficits which can be avoided only by conventional energy resources until a replacement energy supply that ‘adds up’ is created.

Disclaimer: This is a back-of-the-envelope calculation based on published, referenced data. The calculations depend on the stated assumptions. The interested reader may revise these BOEs with their own assumptions.

Keywords: energy policy, electricity, wind energy, wind turbines, wind, solar, renewable energy, capacity factor, cost of electricity, energy restoration

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Published xxx

Publicly available at



Selected Abbreviations

- BOE – Back of the envelope
- CCUS – Carbon capture utilization and storage
- CF – Capacity factor
- CSP – Concentrated solar power
- DR – Dynamic reserve
- ERR – Energy extraction and restoration rate (also called energy rate of restoration)
- eROI – Energy return on energy invested (also often referred to as eROEI)
- EV – Electric vehicle
- GH – “Green” hydrogen
- GHG – Greenhouse gas
- GW – Gigawatt, 1.000 MW or 109 watts (power unit); 1 TW, terawatt = 1.000 GW
- HELE – High efficiency, low emission
- HFNT – hydrocarbon fueled and nuclear thermal power plants
- IEA – International Energy Agency in Paris
- MTOe – Million tons of oil, equivalent
- PA – Peak-to-average power ratio
- PE – Primary energy (PES = primary energy supply)
- PV – Photovoltaic
- T-C – Tri-cellular circulation of the atmosphere
- TWh – Terawatt-hour, 1.000 GWh or 1012 Watt-hours; PWh, petawatt-hour = 1.000 TWh
- VRE – Variable renewable energy, such as wind and solar
- WT – Wind turbine
- ~ – Approximately

Contents

Abstract	1
Preface	3
1. Introduction	3
2. An overview of wind and wind turbines	4
2.1. The total wind resource and its distribution	4
2.2. Actual wind speed distributions and optimum wind turbines (WTs)	5
2.3. Wake effect: a regional climate effect	6
2.4. Wind energy extraction and restoration rate -- ERR: A regional climate effect	6
2.5. Capacity factor versus energy output for wind turbines	7
3. Germany's accessible wind power resources	8
3.1. The Wind always blows, and the Sun always shines, somewhere	8
3.2. Transmission and power conditioning losses for wind turbines	8
3.3. Working life of wind turbines	9
4. Germany's power demand and realistic capacity for wind installations	9
4.1. Calculating required land area for wind in Germany	10
4.2. Feast and famine	11
4.3. The short-term fluctuations in wind	12
4.4. The summer-winter conundrum	12
5. Simple check: why wind plus PV cannot power Germany at today's energy intensity	14
6. Ecological and climate hazards associated with wind farms	14
6.1. Birds and bats	14
6.2. Insect mortality and magnetic fields	15
6.3. Climate consequences of wind, and PV	15
6.4. Energy poverty due to wind and solar PV	16
6.5. Greenhouse gases and global warming	16
7. Commodity requirements	17
8. Backup Requirements	18
9. Conclusions	18
References	20

Preface:

Energy (in Watt-hour or Wh, in German “Arbeit oder Energie”) vs. **Power** (in Watt or W, in German “Leistung”)

- Energy is the capacity to do work. Power is energy per unit of time. Thus, energy is what makes change happen and can be transferred from one object to another. Energy can also be transformed from one form to another. Power is the rate at which energy is transferred.
- Once you know both the energy storage capacity (i.e., MWh) of a battery and the output power (i.e., MW), you can simply divide these numbers to find how long the battery will last.
- Energy is stored in a Tesla battery (i.e., 100 kWh). However, “Horse-”power, let’s say 150 kW, is what moves the car forward. The battery, filled with energy (kWh), drains over time depending on how much power (kW) is required for moving the car, which depends on how you drive and the surrounding conditions.

Capacity Factor “CF” (in German “Nutzungsgrad”) is the percentage of power output achieved from the installed capacity for a given site, purely based on natural conditions. The natural capacity factor does not account for technical outages or demand side curtailments.

- Natural capacity factor is not the Betz efficiency factor. Efficiency measures the percentage of input energy transformed to usable energy. For a wind turbine the Betz Law defines the maximum efficiency is 59.2%, but real wind turbines reach 35-45%, not including losses following the rotor, i.e., gears and electrical generation. Natural capacity factor is due to site and natural conditions, and the wind speed at which the wind turbine output is designed to saturate.
- An average annual capacity factor for wind turbines is the annual number of hours when the energy output is the design output, divided by the total number of hours in one year: 8.766 hours. A typical onshore wind turbine has a 20% capacity factor on annual basis.
- It is important to distinguish between the average annual capacity factor and the monthly or better weekly, daily, or hourly capacity factor, which is very relevant when keeping an electricity system stable that requires demand to always equal supply, every second, for the electric frequency to remain stable.

Entropy of Energy – the 2nd Law of Thermodynamics essentially distinguishes between useful energy (low entropy) that can perform work and less useful energy (high entropy) that cannot easily perform work.

- Entropy is a measure of randomness, disorder, or diffusion in an energy system where greater disorder equals greater entropy.
- Whenever energy is converted from one form to another, there is always a fraction of useful energy that becomes useless (entropy / disorder increases).
- Planck said in other words: *“Every process occurring in nature always increases the sum of the entropies of all bodies taking part in the process, at the limit – for reversible processes – the sum remains unchanged.”*
- The 2nd Law of Thermodynamics thus explains why perpetual motion machines are not possible.
- Thus, the more complex energy processes are, the more useful energy is lost.

1. Introduction

The public declarations of German Minister for the Environment, Ms. Svenja Schulze, at COP 26 in November 2021 and earlier in March 2021 at the anniversary of the Fukushima nuclear plant disaster, that Germany will abandon coal and nuclear energy require validation by a data-based analysis of wind energy for Germany (Deutsche Welle 2021, CleanEnergyWire 2021). The Minister stated *“We will rely completely on energy derived from solar and wind.”* The IEA asserted in May 2021 that *“Solar power will become the new king of the world’s electricity markets”* (IEA 2021a). These statements motivate our present effort to extend our earlier back-of-the-envelope (BOE) calculation on Solar in Spain (Schernikau and Smith 2021) to the combined photovoltaic and wind turbine replacement of 100% of German electrical power. Schernikau and Smith 2021 presented a data-based, BOE estimate of the PV-park in Spain which could reliably provide just over 15% of the electrical power demand for the EU or 100% for Germany.

The IEA asserts, in its May 2021 *“Net Zero by 2050”* pathway that an increase of solar and wind global electricity from its current share of ~8% to almost 70% must occur before 2050 to reach “Net-Zero” CO₂ emission (IEA 2021b). “Net-Zero” greenhouse gas (GHG) emissions are not targeted by the IEA since CH₄ emissions are not included even though IPCC metrics indicate that CH₄ in terms of CO₂ equivalents is more important than CO₂ (Schernikau and Smith 2022a). Since hydrocarbon fuels and vehicles using hydrocarbon fuels are to be eliminated before 2050, a realistic global BOE calculation includes the energy demand for transport.

Photovoltaic (PV) parks and wind turbine (WT) farms are usually assumed to be complementary capabilities in a combined energy transition. That assumption is examined here from the data. The public statements, as above, assert that PV-Wind systems will provide nearly all of the energy resources to replace Germany’s total energy requirement, not only electricity, so we proceed on that assumption. Our present effort is to specify, if possible, a combined wind and PV plant which is viable, sufficient, and stable enough to supply 100% of Germany’s near future energy requirement as electricity, or, equivalently, ~15% for the EU. The reliability of the system should be as good as or better than the energy supply available prior to 2000. Apparently, this analysis has not been carried out, based on data, despite the expenditure of hundreds of billions of Euros in its development. The reader can extrapolate the results from this paper to other regions in the planet, making their own assumption, but using the same framework.

Our World in Data shows that Germany consumed an average 3.550 TWh of total primary energy (305 MTOe) p.a. from 2016 to 2019 (OurWorldInData 2022). Germany’s electrical energy demand averaged 515 TWh, or about 15% of its primary energy consumption. Assuming Germany would average 40% electricity generation efficiency, 515 TWh of electricity would require about 1.300 TWh of primary energy (or 36% of total). The 515 TWh translates to an average power demand of just under 60 GW. The authors analyze what it would require, based on existing data, to produce the entire power demand from wind alone. Then, also based on data, we estimate the combined PV-wind required to match German total energy demand.

2. An overview of wind and wind turbines

Wind originates from the changes in air pressure from place to place in response to solar insolation. The simplest wind, the pressure gradient wind, arises from the atmospheric pressure gradients, e.g., between the warm equator and the cold poles.

This pressure gradient converts primary solar heating into a secondary energy, the wind. The pressure gradient and the Coriolis force, due to the rotation of the Earth, combine with turbulence to create the tri-cellular model for circulation (T-C), with one tri-cell in each hemisphere (GeographyNotes 2022).

The T-C circulation winds, in principle, contain enough energy to drive the wheels of civilization if they can be converted into electricity sustainably and reliably in the energy transition away from conventional fuels: oil, coal, gas, and nuclear. Nuclear energy is to be eliminated in the energy transition in Germany. We do not discuss the rationale for the energy transition, only if it can be done.

Extracting energy from wind is not a new idea as wind power has been used, for millennia, to grind grain, to pump water, and to move ships (EIA 2022, Eldridge 1980). Electricity, produced from wind turbines, is a more recent development. While practical windmills have been in existence for hundreds of years, the thermodynamics and operational aspects of wind turbine technology were derived within the past century by Betz who determined the maximum efficiency, C_p , of an ideal wind turbine to be 59,2% (Betz 1926). The Betz efficiency is not related to the capacity factor or utilization factor, see below, but optimizes power extraction from the wind. Thus, technological improvements strive to get as close as possible to this maximum Betz efficiency.

A wind turbine (WT) extracts power, P , given by the volumetric flow of air through the turbine, multiplied by its Betz efficiency, C_p , for the wind turbine design, according to below Equation 1, where ρ is the air density, A is the turbine rotor area, and V is the wind speed. A thorough discussion is given by Olauson 2014.

$$P = \frac{1}{2} C_p \cdot A \cdot \rho \cdot V^3 \quad (1)$$

Engineering realities, such as structural rigidity, rotor distortions, trimming of the rotor for wind speed, among many variables, reduce the real-world efficiency well below the Betz Limit (Royal Academy of Engineering 2022). At the optimum design wind speed, high speed wind turbines may achieve “peak efficiency” of 35% to 45% for energy extraction to the turbine, declining at wind speeds above and below the optimum. The components that convert the rotation of WT rotor to electricity, i.e., gearboxes, bearings, generators, etc., further reduce the electrical output of the WT to between 10-30% of the raw wind power. A wind turbine’s installed power of 10 MW (electricity) then requires 30-100 MW of raw wind power. Below, we will learn that the continual extraction of raw wind power will have a specific physical limit.

A wind turbine placed in a typical wind will achieve a capacity factor (CF) equal to the annual number of operating hours at the “installed power” output divided by 8.766 hours/year. The CF is site specific and independent of the technology used. Wind farms aim at optimization of energy extraction for a given site’s wind field, but since all wind fields constantly vary, compromises are required.

MacKay 2009 discussed wind power in the UK prior to 2009. The authors, here, extend MacKay’s analysis to Germany, particularly with regard to the developing experience with offshore wind turbines during the past decade.

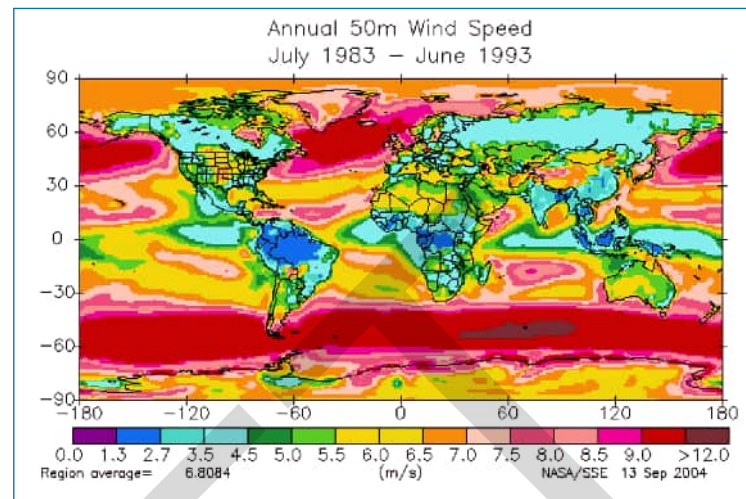


Figure 1: Mean speed and distribution of the global wind resource
Source: NASA 2022

2.1. The total wind resource and its distribution

There are five quantities we assess from manufacture’s specifications and from real data:

1. Installed or nameplate capacity of a wind turbine or wind farm.
2. Energy produced at specific wind farms over a known time interval.
3. Usable energy actually delivered to a customer.
4. Self-induced effects on the long-term output of large wind farms.
5. The theoretical potential of the wind energy resource for Germany, using existing data from available areas on- and off-shore.

Wind is a global power resource, estimated to lie between 45 and 100 TW (Adams and Keith 2013). This may be compared with the global human average power demand of ~20 TW (~170.000 TWh/8.766h). The estimated global wind, in principle, can meet the present global average power demand; with emphasis on the average. We also seek to answer whether this replacement is possible in practice.

The global distribution of wind speed (Figure 1) shows that the highest wind speeds at a 50-meter hub height lie between about 35 and 65 degrees north and south latitudes, primarily over the ocean relatively far away from highly-populated areas in Asia and Africa. This is similarly true for the optimum hub height of 150-200 m (see Figure 5). Distant ocean locations render much of the potential wind resource inaccessible at present. We focus here on Germany which borders with high-wind areas in the North Sea and Baltic Sea. Europe’s wind resources are shown in Figure 2, the color scheme is reversed from

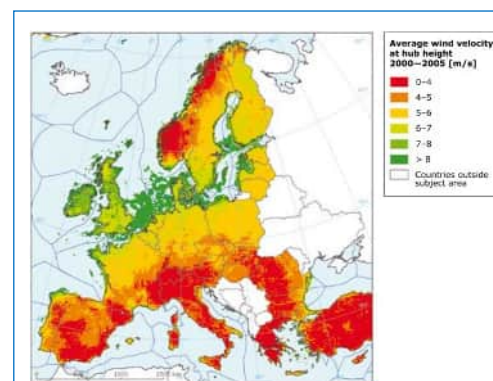


Figure 2: Wind speeds in Europe

Note: ECMF wind field data after correction for orography and local roughness (80 m onshore, 120 m offshore)
Sources: Adams and Keith 2013, EEA 2009, p16, map 2.2

Figure 1). The wind resource declines from the North Sea/Baltic Sea toward Southern Germany, ranging from a wind speed over 8 m/sec to a hardly useful 4 m/sec at hub height.

The wind distribution appears nearly the inverse of the solar resource for photovoltaics (PV) which tends to increase toward the South in Europe (Schernikau and Smith 2021). This inverse relationship suggests the possible specification of a viable PV – wind energy system to match Germany's total power requirement. We will explore this possibility herein.

To turn raw wind into usable electricity, we require a conversion of wind speed into electrical power output using Equation 1. To provide electrical output in W/m² (equivalently in MW/km²), we next apply the Weibull wind speed distribution and the essential aspects of WT design to extract electrical power from wind.

2.2. Actual wind speed distributions and optimum wind turbines (WTs)

The Weibull wind speed distribution (Weibull 1951) is plotted as a dashed line in Figure 3 and follows closely the typical speed distribution of winds found globally.

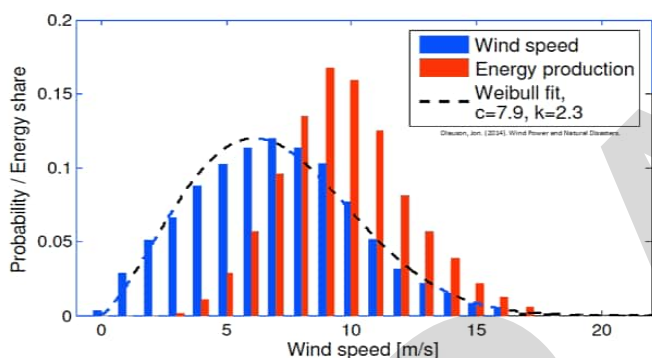


Figure 3: Weibull wind speed distribution curve

Note: Power extraction curve is plotted against Weibull curve (colored). Histogram and Weibull fit of wind speed probability and energy production share. The measurement is taken 100 m above ground, mean wind speed is 7 m/s containing about 250 W/m² of WT area (swept). Energy production in the plot is calculated for Vestas V90 2 MW.

Source: Weibull 1951, Olauson 2014, p10, Fig 2.1

The cubic dependence of power output on the wind speed (Equation 1) causes the rapid increase in electrical energy production in Figure 4, for clarity depicted in red (Hoogvijk 2008). The red line shows the power output for an unshrouded, isolated wind turbine (WT) in a Weibull wind speed distribution. A WT output is designed to saturate at a specific wind speed, usually near 12 m/sec. According to Equation 1, **a wind turbine in a 17 m/sec wind should yield 22 times more electricity than the same wind turbine in the mean 6 m/sec wind.** However, past the saturation wind speed, the modern WT electrical output is held nearly constant by adjusting the rotor

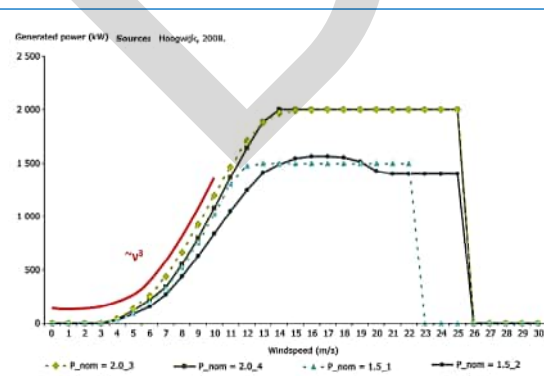


Figure 4: Power-velocity curve of four existing wind turbines

Note: The red line, displaced upward for clarity, shows the power output for an unshrouded, isolated wind turbine (WT) in a Weibull wind speed distribution

Source: Smith based on Hoogvijk 2008

shape and orientation. This necessary technical manipulation logically results in a loss of efficiency. Rotor control permits operation of the WT in wind speeds up to 25 m/s without destroying the WT. As wind speed increases above ~25 m/s, the WT is usually turned off to avoid its destruction.

For the Weibull wind distribution, the energy output of a well-designed WT (red bars in Figure 3) is skewed toward those time intervals with high wind speeds. WT power, thus, is highly variable because of the typical wind speed distribution (See Section 4.2). The physics embodied in Equation 1 dictate that little power can be produced at wind speeds below 5 m/sec. A wind turbine could easily be designed to operate in a 5 m/s wind at high capacity factors, but the energy output would be very low. **An efficient wind turbine is the compromise dictated by the Weibull wind distribution and the optimization of the energy output.** In this aspect, a wind farm is very different from a PV park. At a high grid penetration, wind farms could be designed to meet the average power demand for the median wind speed, but would produce excess electricity in high-wind periods. Application of the excess electricity to electrolysis of “green” hydrogen (GH) or pumped hydro, could, in principle, provide back-up when the wind speed is minimal or null, as is discussed later.

Measured ocean vertical wind speed profiles define the optimum hub height (Figure 5, Probst and Cardenas 210). Wind speed typically increases with altitude to over 150 m after which it stays approximately constant up to the boundary layer. The wind shear (speed variation with height) is usually smaller offshore than onshore. This produces less torque on the WT and higher energy output for a given turbine structure. Turbines of 10-12 MW nameplate capacity have rotors approaching 100 m lengths, placing the hub near 150 m. With the rotor sweep above 50 m, probable waves are no danger. It would be interesting, however, to consider the result of a 26-meter rogue wave, such as the Draupner North Sea Oil Platform Wave in 1996, striking a wind turbine tower designed to withstand 10-meter waves (Chabchoub et al. 2012). Presumably, that would be a rare occurrence.

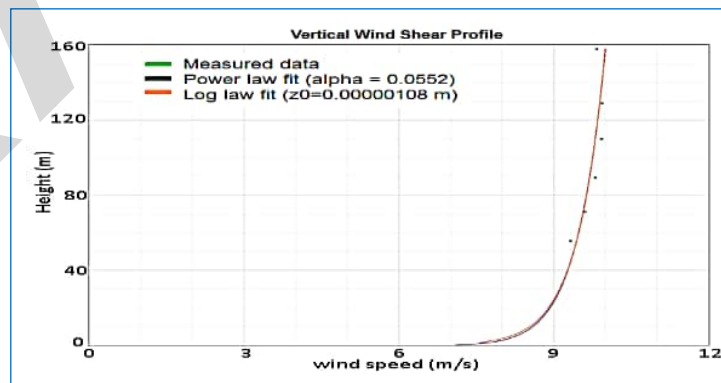


Figure 5: 15 month average ocean vertical wind profile

Source: Smith based on Nierenberg, et al. 2016

2.3. Wake effect: a regional climate effect

The downstream wake effect of wind farms has received detailed study (e.g., Akhtar et al. 2021). A capacity factor loss of between 20% and 50% can occur due to wind suppression, and rotor induced vortices, following the first WT row. **To minimize wake losses, a wind turbine spacing of 15 turbine rotor diameters is recommended from wind tunnel studies** (Meneveau and Meyers 2011). In addition to agreeing that the optimum spacing is 15 WT rotor diameters in along and cross wind directions, altering the wind angle to the WTs and intentional reduction in the output of the first row of WTs is shown to produce a higher overall wind farm power level (Porte-Agel et al. 2013). Existing wind farms do not meet these optimization criteria. The number of WTs per km² scales with the diameter of the WT rotors for a given spacing as WTs become larger. This means the extractable power per km² remains approximately constant despite technology improvements, since larger WTs need to be spaced further apart.

Current typical wind farm turbine spacing varies, but the rule of thumb for onshore is five times the rotor diameter between the towers in the main wind direction and three times the rotor diameter in the side wind direction (KNE 2022). Offshore appears to show less than 6x rotor spacing, such as Germany's Hohe See and Albatros (EnBW 2019).

2.4. Wind energy extraction and restoration rate (ERR): A regional climate effect

Offshore wind farms are expected to produce more electricity per square meter than onshore wind farms due to higher mean velocity winds. MacKay 2009 estimated a yield of 3 MW/km² of electricity for offshore wind farms compared with 2 MW/km² of electricity for onshore farms. MacKay's estimate is based on early experience in UK wind farms. Because at the time of writing his book, wind farms were not yet very large, MacKay did not consider including replacement of energy extracted from the wind at larger grid scale wind farms. Laws of energy dictate, the energy extracted by the WTs must be replaced or the wind stops.

The wind energy restoration rate (ERR) limits wind energy extraction in large wind farms (Lorenz 1955, Miller and Kleidon 2016, Porte-Agel et al. 2013, Adams and Keith 2013).

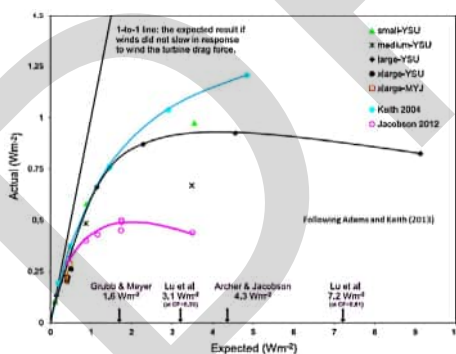


Figure 6: Actual vs. expected wind farm output
Source: Smith based on Adams and Keith 2013

It is an energy conservation law that continuous energy extraction must equal the kinetic and potential energy moving downward from upper atmospheric levels. ERR, then, is determined by the available atmospheric "potential" and "kinetic" energy. Lorenz 1955 analysis gave an energy restoration rate ERR of ~1 MW/km². Subsequent mesoscale model analyses following Adams and Keith 2013 (Figure 6) shows the installed power density in W/m² (equivalent to MW/km²) versus achieved power density, for both experiment and theory.

The experimental data sets (blue-magenta in Figure 6) show a dramatic effect of the ERR limit as the deviation of the plotted points. We have added lines through the data points to point out the rapid decrease from the 1:1 no-wind-saturation-line. There is also qualitative agreement with theory. The power extraction curves lie between 1,25 W/m² (= 1,25 MW/km²) and 0,5 W/m², as expected from Lorenz 1955 analysis and from climate models at macro-scale, referred to in Adams and Keith 2013. **Wind's energy extraction and restoration rate ERR causes declining energy returns, in other words, declining capacity factors, for larger wind farms** where wind turbine spacing is less than 15x rotor diameter. This issue of declining capacity factors for large wind farms, not present for an isolated WT, has been demonstrated by Miller and Kleidon 2016, Miller and Keith 2018, Rodrigues et al. 2018, Agora 2020, WindAction 2018, Musial 2018.

Figure 7 illustrates the sequence of limits imposed on extracted energy from an isolated WT to a large wind farm (Agora 2020). **The extraction of wind power is decreased to ~1,2 MW/km² by wake turbulence and limited by ERR**, to the transfer of potential and kinetic energy from the atmosphere. This power extraction density is smaller than the typical installed wind turbine power density. Agora 2020 specifically lists installed wind turbine power densities between 7,5 and 12,5 MW/km², and anticipates – in the authors' view mistakenly – capacity factors between 35% and 59%, depending on the mean wind speed in selected areas of the North Sea. The lower capacity factor of 35% is achieved if only the German Bight "Deutsche Bucht" in the North Sea of Germany is used (an area of 7.200 km²).

The German Bight installed wind turbine power density is seven times larger than the power densities that the data and physics define as feasible for continuous power extraction in MW/km².

Using the Agora's capacity factor range above of 35% to 59%, the minimum power per km² is $0,35 \times 7,5 = 2,6$ MW/km², and the maximum is $0,59 \times 12,5 = 7,4$ MW/km². AGORA 2020, page 15 of 84 acknowledges that the German Bight option electrical output will fall to $(35/59) \times 100\% = 59\%$ of the capacity factor achieved in an area twice as large. This is due to WT crowding, in other words, too many WTs in too small an area. As MacKay 2009 warned, achieving renewable power/energy replacement requires country-sized facilities, which we now understand can only be accommodated within crowded countries by over-withdrawal of wind energy by a large excess of wind turbines.

Since energy is extracted from the wind, plausibly, wind farm electrical output is limited by the ERR and wake effects (Section 2.3). To meet the demands of the "energy transition", wind farms must grow in size by many thousands of km². Christiansen et al. 2022 and Miller et al. 2015 generally agree that achievable electrical power withdrawal is limited by ERR (Figure 7), in the case of Miller et al. 2015 to about 1 MW/km².

In Europe, including Northern Germany, the plan is to install power densities exceeding 20 MW/km². Wind farms in the USA, where space is not so limited, have installed wind turbine power densities of ~3 MW/km² (Aweo 2022). WTs of 12 MW and even 25 MW nameplate capacities and hub heights of 200 meters are taller and larger than their predecessors. These sizes and heights impact energy production as the wind farms fill onshore and offshore areas and influence each other. As discussed, wind farms, by direct measurement, suffer as much as 27% losses from these collective phenomena.

The larger wind farms of the future are expected to suffer greater losses due to ERR and wake effects. The areas available for wind farms must be increased and enough wind turbines must be installed, even with CF reduction, to meet the total power demand. This scenario also has economic consequences which we will not discuss. Efforts to circumvent land and sea exclusions, due to environ-

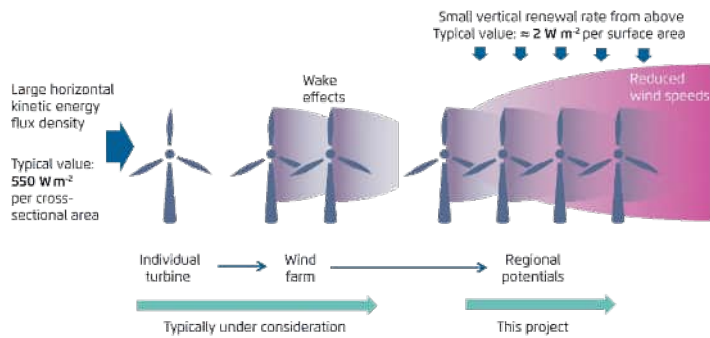


Figure 7: Illustrating wake effect and energy rate of restoration (ERR)
Source: Agora 2020, Figure 6, p16

mental and other considerations, are already underway in Germany. Some scenarios increase the land area for wind energy development to as high as 50,000 km² or 15% of Germany's land area, not considering that Germany's wind resources are not evenly distributed across the country (Agora 2020, Naturschutz 2020).

In conclusion: **Wind turbines should maintain a 15x rotor diameter spacing in all directions. Therefore, the electricity generation from wind per km² is nearly independent of the WT technology employed.** Repowering existing smaller WTs with larger WTs at the same wind farm site must increase the effective spacing to keep the overall wind generation essentially unchanged per km². If larger WTs reach more favourable winds as the hub height increases, then an output gain is possible.

2.5. Capacity factor versus energy output for wind turbines

Equation 1 defines the maximum extraction of energy from a wind stream as a function of wind speed, recognizing the Betz efficiency, C_p , is not a constant. The simple capacity factor, or load factor, for a wind turbine is defined as the number of "full load" hours, in other words hours operating at or above the saturation wind speed, divided by 8.766 hours in a year (see also Hoogvijk 2008). **This capacity factor for wind, which is limited by natural availability of wind, cannot be compared to the plant load factor (PLF) of a conventional power plant**, which is limited by technological outages or reduced consumption requirement. One would have to multiply the wind capacity factor with the wind "plant load factor" caused by technological outages or reduced consumption requirement to make the two comparable.

Since the Betz efficiency factor, C_p , declines for wind speeds above and below the design saturation wind speed (see Figure 4), the flat "full load" achieved at a wind speed near and above 13 m/sec imply a decreasing efficiency factor, and consequently a decreasing net efficiency. This is evident since the output, based on wind velocity alone, would be eight times higher for a doubled wind speed for a constant C_p , if the WT would not adjust its rotor shape and orientation to keep electrical output near constant. In fact, the Betz efficiency factor is altered by changing the pitch or shape of the rotor blades to maintain the so-called "full load" or saturated output. The CF, then, is the fraction of hours annually operating at the "full load" output. The Weibull wind speed distribution is sufficiently general so that median wind speed can be used from site to site as a design variable. A 6 m/s median wind for the Weibull wind speed distribution, then, yields 2.000 hours of "full load" capacity for a wind turbine designed to saturate at 13 m/s, or a 23% capacity factor (2.000h/8.766h p.a. = 23% as detailed in Figure 8)

Here, the relatively wind-rich year 2020 is our base year to calculate CFs for Germany, which operated 30.000 WTs. The data is extracted from Naturschutz 2020, StiftungKlima 2022, KNE 2020, Fraunhofer 2012, Umweltbundesamt 2019, Smith 2022.

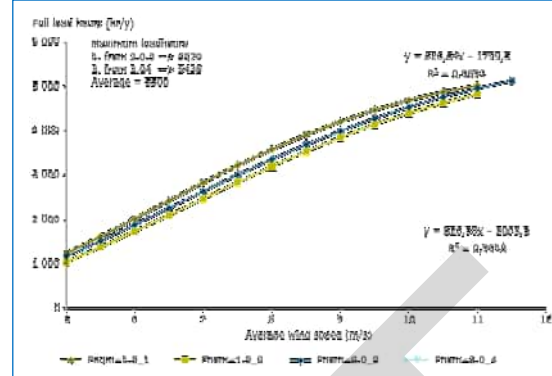


Figure 8: Wind speeds and actual capacity factors and wind speeds
Source: Hoogvijk 2008, Fig. 2.3 in EEA 2009

Onshore: In 2020, Germany averaged a nameplate capacity of 2 MW, rotor diameter of 120 m, sited on ~1.800 km² of land (Agora 2020) for an installed power density of 33,3 MW/km², corresponding to generated 7,3 MW/km² for the attained 22% capacity factor at the wind farm.

The wind farms presently cover 0,5% of German land area, but the wind turbine itself covers a relatively small space. Less than 5% of the wind farm site consists of access roads, power couplings, transmission stations, and more (Diffendorfer and Compton 2014), the remainder of the wind farm site, after construction and before demolition, is available for other purposes such as crops or normal infrastructure. This low WT footprint is an advantage over PV parks which essentially cover the entire land area. We will consider this aspect later. During construction and demolition of a wind turbine, lasting approximately 3-4 years or 15% of the average wind turbine's life (Christol et al. 2021), a larger area of a wind farm is unavailable for other uses. Living beneath a wind turbine is essentially impossible due to high and low frequency noise, rotor shadow flicker, ice throws, rotor failure and tower collapse.

The German installed WT power density multiplied by the CF of 22% onshore still significantly exceeds ERR as well as MacKay's more generous 2 MW/km² for onshore wind farms. The fact that over 7 MW/km² of electricity were reported as generated on average is contradictory to MacKay 2019. At this point, a fair question to ask is: Have onshore wind turbines in Germany generated as much electricity as expected or projected?

The answer is that they have generated 73% of the expected electricity, according to Germer and Kleidon 2019. The 27% shortage in average electricity generation was ascribed by the researchers 70% to unknown causes and 30% to age and park effect related losses. If the 19% (27% x 70%) discrepancy is due to over-withdrawal, then the discrepancy will grow in the future as wind farms grow. That is, the installed capacity times CF will trend downward toward the ERR (Figure 7) which is physically logical.

Offshore: In 2020, Germany's 1.500 installed offshore turbines had an average 5 MW nameplate capacity at an installed power density varying between 5-11 MW/km². They occupied between 800 and 1.600 km² in the North Sea and Baltic Sea, respectively (Agora 2020). This installed power density offshore is higher than the continuous wind energy withdrawal values noted in Section 2.4. Assuming a typical 37% capacity factor, the withdrawal is 1,5x to 3,4x higher than ERR. This withdrawal portends CF declines as the wind farms fill the selected optimum offshore sites. The Agora 2020 analysis applied to ~7.200 km² in the German Bight, states the wind resource will decline substantially as the available energy is overdrawn. The cited studies confirm that lower than anticipated electricity output will occur in the wind park size regime >100 km², a size regime now being entered. The proposed North Sea wind farms will achieve ever lower energy returns as they fill in the German Bight.

Germany's 2020 total installed (nameplate) wind capacity was ~54,6 GW onshore and ~7,7 GW offshore. In Germany, wind produced 132 TWh of electricity in 2020 (~25 TWh from offshore). The sum of solar PV plus wind produced ~183 TWh of electricity. PV contributed 51 TWh from an installed PV capacity of ~54 GW.

Using these numbers, Germany achieved average annual capacity factors for wind in 2020 as follows (Agora 2020, KNE 2020, Fraunhofer 2022, Umweltbundesamt 2019):

- Wind (total) 132 TWh / (62.3 GW x 8.766h) = ~24%.
- Offshore wind 25 TWh / (7,7 GW x 8.766h) = ~37%.
- Onshore wind 107 TWh / (54,6 GW x 8.766h) = ~22%.
- German PV 51 TWh / (54 GW x 8.766) = ~11% ~~capacity factor.~~

The capacity factors vary significantly from year to year as was witnessed during 2021 when wind output decreased in Northern Europe significantly compared to 2020 despite continuous increase in installed capacity. The fraction of the renewable energy electricity that reached a German consumer is calculated in the following Section 3.

3. Germany's accessible wind power resources

To replace fossil and nuclear energy by off- and onshore wind turbines in Germany, let us assume 10 MW wind turbines would be installed universally. Larger WTs exist, but the power density and area required of WTs to match Germany's current energy demand scales with WT size, as shown above, and therefore little benefit derives from larger turbines when it comes to optimizing space. The point is to develop offshore wind to the maximum possible, plus sufficient onshore capacity to make up any deficit. The reader may choose any ratio desired. We will consider only physical, not financial, political, or cultural factors.

To be acceptable, the proposed wind turbine electrical power system must meet the current German electrical energy demand with the same reliability experienced under the fossil fuel and nuclear regime which is being displaced. The electricity output must also grow, since the German Energiewende or "energy transition" dictates a future where electricity shall also be used for all heating, transport, and industrial demands.

3.1. The wind always blows, and the sun always shines, somewhere

This section heading is a statement that is true, but irrelevant. Interconnection among two equal, distant, anti-correlated wind farms is a proposed solution to wind variability. However, the global correlation of wind speed with a point in Germany (EIA 2021) in Figure 9 shows that anti-correlated wind farms must be inter-hemispherical. Weather patterns in the polar front of the northern hemisphere T-C circulation are highly correlated. Thus, Europe and the North Atlantic Ocean have a 3:1 probability of having too much or too little wind at the same time. The wind speed data show that optimally stable wind power requires electrical power transmission over distances much greater than 5.000 km. Anticorrelation does not imply that the wind speed is high at opposite times. For example, wind in the Sahara is anti-correlated with wind in Europe, but the Saharan wind resource is rarely more than marginal according to Figure 1. The Sahara's "renewable" resource is photovoltaic or concentrated solar power (CSP) but not wind. Power transmission lines of 10.000+ km are not feasible at present (see below).

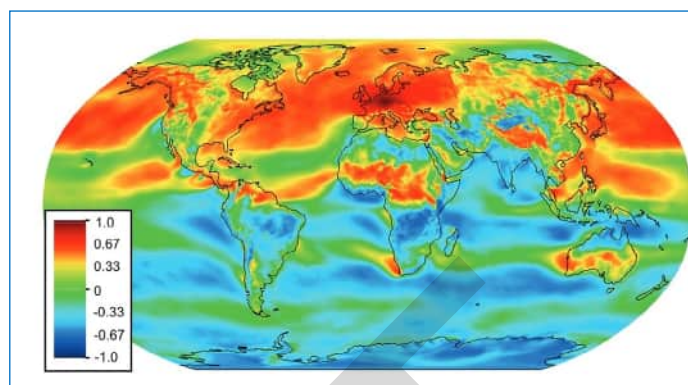


Figure 9: Correlation in 30-day wind speed to a grid point in Germany.

Note: Based on 10 years of Merra Data
Source: Olausen 2014

If two widely separated wind farms are constructed, then, the transmission infrastructure size, distance, and losses also more than double. Each wind farm must be much larger than a single wind farm in Germany since each must now produce sufficient power to meet both the local and the remote power demands, including peak load, safety margin, storage, and backup. Power must be able to flow freely in both directions. Local demand would be satisfied first and excess power could be shipped elsewhere. "If the wind stops at both sites, a small but not negligible possibility even if the wind farms are 10.000+ km apart, then the entire grid would collapse. Any other power sharing arrangement would be unacceptable, unfair, and unequal. This situation has already occurred. Sweden acted to protect its own grid against Norway and Poland by inhibiting meeting external demand (Bloomberg 2021). Arizona's electricity, bought in Oregon, was hijacked by California during a recent California power shortage (Independent 2021a). Such situations can and have produced serious conflicts, even among friendly countries.

3.2. Transmission and power conditioning losses for wind turbines

The proposed Euro-Asia Interconnector Project 18 would deliver 2 TW of power from the Northern Territory of Australia to Singapore, a sea distance of 4.500 km (EuroAsia Interconnector 2017). If ever built, the project will demonstrate very long-distance submarine power transmission. **Less than 60% of the power fed into the system in Australia is expected to reach the consumer in Singapore**, according to the design specification. That is, 2 TW delivered compared with a 3,3 TW source capacity. Such losses are unavoidable to produce a reliable, sufficient, and stable supply of electrical power between on- and offshore wind farms and the consumers. If one were to transport the power in the form of hydrogen, then additional energy would be required to store and transport hydrogen. For more details please refer to Schernikau et al. 2022 on Full Cost of Electricity ~~ECOE and eROI~~.

When undersea cables fail, the EEA 2009 notes, the lines are typically out of service for months. A deep-sea cable such as the Euro-Asia Project would also be subject to turbidity currents which have repeatedly broken communication cables between Europe and North America (ScienceDirect 2011).

Transmission and distribution losses discussed above are in addition to the conversion and conditioning losses which must also be specified. Wind turbines produce alternating current a/c electricity. The alternating current from a WT is not produced at a sufficiently stable voltage, frequency, or phase to insert directly into a grid.

Typically, **an offshore sub-station rectifies and sums the current from individual wind turbines and transmits it to land. A wind farm's rectified electrical output must then be converted to the correct voltage, frequency, and phase, before insertion into a grid.** The voltage is increased to limit resistance losses. Since the power, P , delivered via a transmission line is:

$$P = I \cdot V = I^2 R \quad (2)$$

A higher voltage, V , lowers the current, I , and, in turn, reduces resistance, R , and therefore heating and power loss in the transmission cable. Rectification and then inverter losses result in a round-trip loss of ~30% of the (on- and offshore) wind farm's raw electrical output. Onshore transmission losses alone are usually ~8-10%, depending on the distance from the WTs to the consumer, additional rectification and inverter losses are unavoidable. The transmission lines from deep water or remote land wind resources require high-voltage DC lines to avoid AC reactance losses. The total conditioning plus transmission losses (15% rectification, 15% inverter and ~9% transmission loss, as noted for California by World Bank (2018) or ~33% of the raw wind farm output power, even over the relatively short distances in California. In line with Schernikau and Smith 2021, the authors use a rather conservative transmission and conditioning loss factor, L_{tc} , of only 1/3 to compensate for such losses from the WT raw output to the consumer. Actual losses appear to be significantly higher based on the examined real-life experiences.

3.3. Working life of wind turbines

All machines degrade in performance with time, including wind turbines. The question is how large a decline can be accepted before "repowering".

Onshore UK wind farm capacity factors declined by ~1.7%, annually, in their first 15 years of operation (Figure 10). After 15 years, the overall decline was ~20%; by 20 years, the decline increases to ~50%. Then, 20 years is an upper limit of the lifetime of an onshore wind farm, and repowering after 15-18 years is quite common and appears commercially logical.

Madlener et al. 2019 wrote a detailed study on onshore repowering in Germany and concluded: "We find that repowering well before the plant's expected end of life ('early repowering') can be economically preferable under the German Renewable Energy Sources Act 2017 remuneration scheme...". The researchers confirmed that most repowering projects happen as early as 10 years and as late as 20 years after installation.

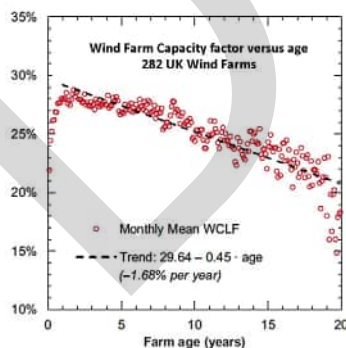


Figure 10: Monthly mean capacity factor decline for onshore wind farms
Note: Data is based on UK onshore wind farms
Source: Staffel and Green 2014

Offshore wind turbines decline faster, possibly as much as ~4.5% annually or up to ~50% after 10 years (EEA 2009, Manhattan Institute 2020), thus, replacement or "repowering" would have to occur earlier.

These numbers are approximate and require further study, but there is little doubt that offshore WTs will not last as long as onshore WTs due to rough and aggressive sea conditions. A rapid decline in offshore CFs places a premium on the development of materials and designs which slow the offshore deterioration. Materials are already designed for harsher ocean environments, but do not match the lifetime of onshore WTs. The more rapid deterioration of offshore wind farms implies increased maintenance and replacement costs, as well. For the wind industry "repowering" effectively means "replacement".

Since the best wind sites are those first populated with wind farms, replacement of outdated wind turbines with new and more efficient technology after no more than 20 years is just common sense. However, the authors note that **"repowering" to larger wind turbines usually means that the spacing of the wind turbines is not increased, thus their net efficiency after accounting for wind energy and restoration rate ERR will not match design capacities** but be much lower (see Section 2.4). This will become even more relevant for larger wind farms built in recent years or planned in upcoming years that are only up for "repowering" in 5-10 years from now.

Fast-paced wind turbine innovation and technology improvements would also encourage "repowering" wind farms earlier than 20 years. The wind industry works under the assumption that early repowering has ecological and economic advantages, and also contributes to increasing "renewable" share in total electricity generation (Madlener et al. 2019). The wind industry, however, in their assumptions does not consider the entire life-cycle and supply chain, net energy efficiency, or eROI (see Schernikau et al. 2022).

For comparison, coal and nuclear power plants routinely achieve a lifespan of 50-75 years with minimal upgrading requirements, 2-4 times longer with relatively slight upgrading investments. They are usually designed to last 40 years without any upgrading required at all. If repowering wind farms every 15 to 20 years makes sense, upgrading coal and nuclear plants to extend their plant life times to 75+ years with modern, ultra-super-critical HELE technology also makes sense.

4. Germany's power demand and realistic capacity for wind installations

Germany required an average 3.550 TWh of total or primary energy¹ (305 Mtoe) p.a. from 2016 to 2019 (Our World in Data 2022, Agora 2022a). In the same time period, Germany's electrical energy demand averaged 515 TWh p.a., or about 15% of its total primary energy demand, averaging just under 59 GW. The production of two-thirds of German electricity by thermal power plants operating at a Carnot efficiency of ~40% consumes 857 TWh or just under one-quarter of total German primary energy. About one-third of Germany's average electrical energy demand, or 5% of its total energy demand, was met by wind and PV. During 2021, a "poor" wind and solar year for Europe, wind and solar reached 28% of average annual electricity demand and made up 5% of Germany's total primary energy¹, despite continuous wind and solar capacity increases every single year (Schernikau and Smith 2022, Agora 2022a, Fraunhofer 2012, AGE 2021).

Electricity demand and supply must be balanced moment to moment. The German diurnal electrical power demand must ramp between ~35 and ~80 GW (Figure 11). The grid is balanced by slowly ramped base power augmented by pumped hydro and gas turbines to provide fast ramping to balance the grid. Meeting the rapidly varying diurnal demand is a complex task made far more difficult by increasing contributions from erratic power resources. The inability to ramp output to match demand, highlights the fundamental difference between dispatchable versus non-dispatchable power.

1. The low primary energy value, among others, has to do with the assumed 100% efficiency of wind and solar electricity when calculating its share in PE. In other words, it is mistakenly assumed that wind and solar electricity generation was converted, conditioned, balanced, and transmitted at 100% efficiency without any losses or energy costs, and at least, at the same efficiency as conventional base power, which is not the case. If one were to assume a more realistic lower net efficiency, the primary energy share of wind and solar would increase and reported total primary energy in Germany would be higher.

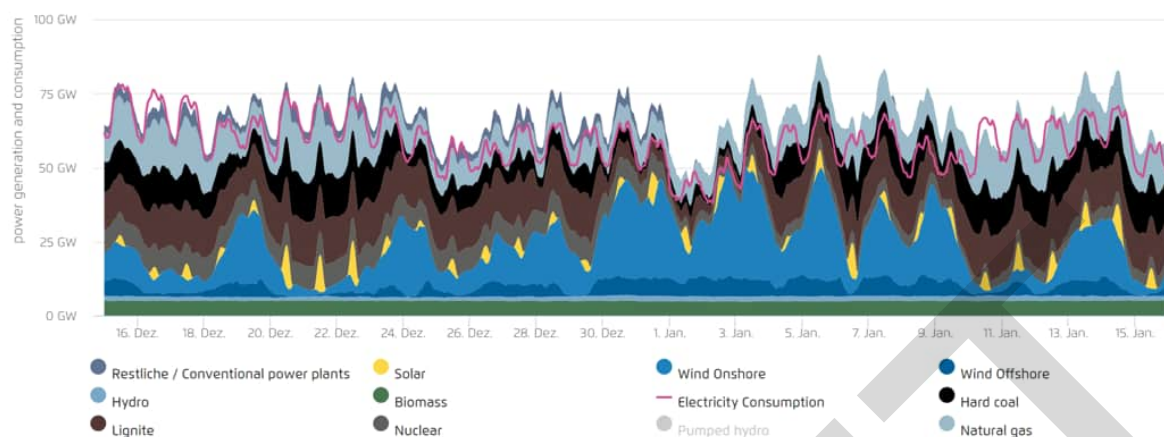


Figure 11: Electricity demand in Germany from mid Dec 2021 to mid Jan 2022

Source: April May 2022 Data, Agora: https://www.agora-energieumwende.de/en/service/recent-electricity-data/chart/power_generation/01.02.2020/29.02.2020/today/

Increasing the erratic power contribution requires a larger fast ramping backup. In turn, this requires a larger base power backup, more computing facilities, more complex and larger transmission networks, control and switching networks, and high-speed power response capabilities because wind and solar power cannot be dispatched at will. These are all well-known facts within the power supply industry and among energy economists.

Normal variations in wind output are manageable as long as large base-power facilities are on standby, and large and fast ramping backups exist.

In addition to the diurnal ramping, the peak-to-average power demand must be managed. Studies of the peak-to-average (PA) power ratio in the Northeastern USA, where climate is similar to that of Germany, found a PA power ratio of 1,8, and PA is also found to be climate and region independent in the USA (EIA 2014). Power grid operators find it expedient and prudent to maintain a dynamic reserve (DR) of 20% above peak demand. Adding this contingency brings PA + DR to 2,2x the mean demand. The 20% dynamic reserve is essential to counter seasonal and daily wind variability, manage units off-line for maintenance and repair, failures of (undersea) cables, and other contingencies. A 20% reserve, available in winter's high winds, disappears in the relative summer calm, as seen in Figure 12 for Danish onshore and offshore wind output from 2003 to 2015. German relative onshore wind capacity factors, plotted over Danish output, illustrate the near perfect correlation (Germer and Kleidon 2019).

Critically, the more than four-year period from 2009 through 2013 resulted in over a 20% reduced wind output for Germany and

Denmark. German offshore wind output fell in 2021, by 11% from the 2020 offshore output. The onshore output drop in 2021 added to the offshore decline and resulted in a 13% overall German wind output loss (Fraunhofer 2022). The multiyear and annual declines occurred even though installed capacity increased by 1,6 GW, as seen in the upward trend line in the Danish output data in Figure 12.

Back to the calculation, to meet the (PA + DR) requirement, the 59 MW average electrical power output should be increased by 2,2x to 130 GW. The wind facility is more than twice as large as required for average operation in order to meet the (PA+DR) criterion. There is no provision for this reality in the current government-sponsored design of the German wind system.

When demand exceeds the wind turbine current output, wind farms can no longer meet the electricity demand without base power support, and load shedding is required. In times of too much wind, the wind resource electrical output may be reduced rapidly by feathering or by use of smart rotors. Rather than curtail output, wind farms' excess output might be converted into "green" hydrogen GH or pumped hydro, and stored as long duration energy backup. Then, dispatch during the frequent wind dropouts, as illustrated in Figure 13 and Figure 15, becomes possible. Wind dropouts are weekly events, requiring sufficient backup to avoid grid collapse or load shedding. The assertion that high penetration wind does not need backup is always qualified and assumes base power exists (see Section 8 for a discussion).

Long-term storage, however, is not needed for thermal or nuclear base power sources, where the stored fuel (e.g., coal or gas) takes over that function. Only a rapid output ramp capability for short

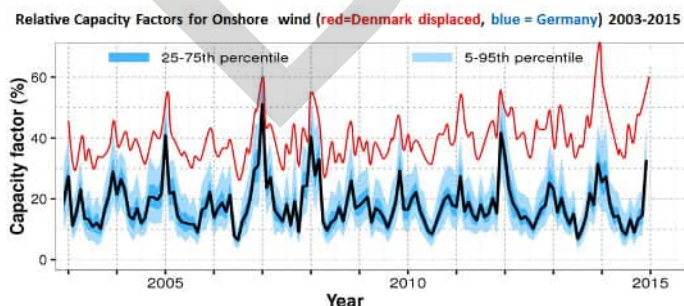


Figure 12: Danish and German wind output correlation 2003-2015

Source: Smith based on and modified from EnergyNumbers 2019 and Germer and Kleidon 2019

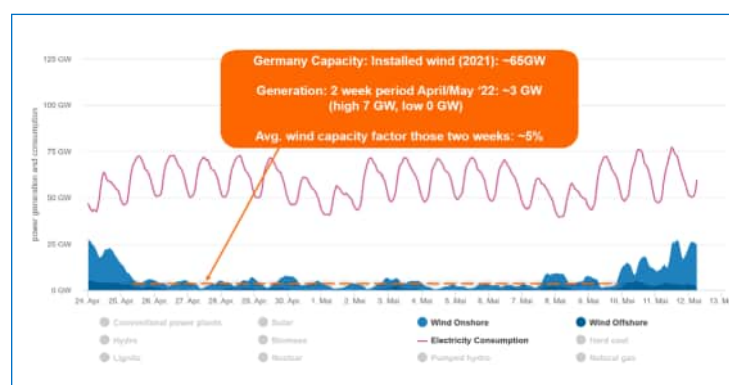


Figure 13: Germany's wind generation 25 April to 10 May 2022, during 2-week wind lull

Source: Agora 2022b

periods is required. Pumped power and high efficiency gas-fired turbines are conveniently used to facilitate fast diurnal ramps while base power is ramped up and down more slowly during a diurnal cycle. This system has worked well for many decades.

4.1. Calculating required land area for wind in Germany

Let us return now to the question of how much wind power can be accessed by Germany. MacKay 2009, in his Table 18.10, suggests a typical “at the plant” wind electricity power output of 2 MW/km² of onshore and 3 MW/km² offshore is achievable, or each 10 MW WT will occupy 5 km² onshore and 3,3 km² offshore. This estimate is based on UK wind farms at sites equal or better than the German wind sites. The estimates are 2-3 times higher than the extraction and restoration rate ERR (Section 2.4) found in both theory and practice that hover around 1 MW/km² as supported by the authors herein and Miller et al. 2015. 15 years ago, the UK wind farms were still small enough that full effects from ERR should not have been encountered and could be disregarded. The effect would have reduced the capacity factors somewhat. Perhaps, the unexplained, but substantial, recently discovered deficit of 27% finds its explanation in ERR (Germer and Kleidon 2019, see Section 2.5). The era of small, isolated wind farms is ending. However, let us use the “stated-to-be-generous” MacKay rule of thumb for our back-of-envelope BOE power calculation below and going forward:

$$P_s = P_p * (A_l + 1,5A_s) \quad (3)$$

Where P_s is power at the site, P_p is installed power density, A_l is the land area and A_s is the sea area multiplied by the 1,5x greater power per unit area of sea over land (MacKay 2009).

First, the German land area required to produce the average 59 GW electrical power demand from a 2 MW/km² wind resource appears to be 30.000 km² of high-quality onshore wind farms, or 20.000 km² of high-quality offshore wind farms, or any combination thereof. Remember, that 59 GW is about 15% of the German gross power demand. Germany is a heavily populated country and 30.000 km² is 8,5% of the total German land area. Such a large area to meet Germany’s present electricity demand may not be available. Various studies (Agora 2022, Naturschutz 2020, KNE 2020, Fraunhofer 2012, Umweltbundesamt 2019, Energy Charts 2022, EnergyNumbers 2022, Staffel and Green 2014) of potential land, as well as offshore areas, for wind farms have allocated a maximum of 2% of Germany, or ~7.150 km², of which the best 1.800 km² in the North of Germany has already been used. Where the additional ~23.000 km² will be found to produce even the present average electrical power is not stated. Some studies (Agora 2022, Naturschutz 2020) have discussed much larger areas, as much as 60.000 km² might be required and allocated.

We discussed and show below that meeting just the average power demand is a guarantee of weekly grid collapses, and that ~130 GW of electrical power is required from the wind facility due to the peak-to-average (PA, 1,8x) and dynamic reserve (DR, 20%) requirement. An additional conservative factor of 1,3x (donated as Ltc) is required to compensate for losses for transmission and power conditioning (Sections 3.1 and 3.2 above). Equation (3) then becomes:

$$P_s = P_p * (A_l + 1,5A_s) * (PA + DR) * L_{tc} = 3,3P_p * (A_l + 1,5A_s) \quad (4)$$

The wind farm area then increases to ~85.000 km² onshore or ~55.000 km² offshore, or a selected mix of on- and offshore wind farms, using the generous assumption of 2 W/m² onshore and 3 W/m² offshore “at the site” electrical output projected by MacKay 2009. We remind the reader that the ~85.000 km² or ~55.000 km² areas meet only the present electricity power demand, not the increased demand from further electrification, nor any non-electricity energy consumption

from heat, transport, or industry.

If we assume the smaller and more realistic ERR of 1,2 MW/km² (Adams and Keith 2014, Lorenz 1955), nearly double the land area is required. In the USA, we note that wind farms average near 3 W/m² (Miller and Keith 2018) so we stay with MacKay 2019.

Further, as detailed in Section 3.3, wind farm output declines with age. Onshore wind farms in the UK declined at 1,7% of output per annum (Staffel and Green 2014). Analysis of Danish offshore wind farms show a 4,5% annual decline (EEA 2009, Manhattan Institute 2020). The 20% dynamic reserve is lost in only 4 years unless maintained by “repowering” or by adding wind turbines to the wind farm. Moreover, the decline of output demands a complete “repowering” of the wind farms within 15-20 years, possibly sooner. An average life span for WTs at grid scale beyond 20 years is not supported by the data.

Accounting now for the annual wind output decline due to aging (Section 3.3), the wind farm area would have to increase gradually, over 15 years to compensate. An alternate solution to the wind farm aging would be the continuous replacement of WTs to maintain the output within a few percent of the initial output; a solution likely favored by the wind farm industry. If that is not possible, the required wind farm area of 55.000 km² (all offshore) to 85.000 km² (all onshore) would need to be gradually increased by about 20% up to between 11.000 km² and 17.000 km² depending on the off- and onshore mix.

The total would then become 66.000 km² (all offshore) to 102.000 km² (all onshore) for Germany’s current electricity requirements only, without accounting for building up storage or backup.

So far, we have been calculating the area for replacement of the present German electrical power only. Since electricity is approximately 15% of the total German energy demand, the replacement of the current annual average total energy demand and replacing it every 15-20 years multiplies the land or sea area, as outlined above, by a factor of more than 6x (total energy is 6,7x higher than net electricity alone, for discussion on primary energy see Footnote 1). **Therefore, the total wind farm area required to replace the present total German energy consumption in the form of electricity – accounting for required reserves, aging, etc. – would be in excess of 350.000 km² if all is offshore, and more than 550.000 km² if all is onshore** (Germany total land area is 357.000 km²), or any combination that meets the demand. Germany does not have such large areas available. Even with strict recycling, supplying the raw material resources and even the energy required to build such wind capacities for Germany is not realistic under any scenario. The authors remind the reader of the closure of a number of wind turbine manufacturers in Germany during the 1st half of 2022 (Focus Online 2022).

Even if such areas were somehow possible, the assumption remains that 100% backup or storage is on standby. In case of storage, the area devoted to renewable energy would increase even more because energy inefficiency of storage has to be accounted for (in case of “green” hydrogen over 60% of energy is lost in producing and consuming H₂, if no transportation or storage of H₂ is required). A wind farm that meets the required peak output at the saturation wind speed cannot meet that requirement during a period of low wind, as shown in Figure 15. Supplemental or stored energy is, therefore, mandatory to stable grid operation. Stable grid operation cannot be achieved without dynamic reserve, adjusting for peak-to-average power demand, or adjusting for aging. Stable grid operation and the corresponding backup requirement is discussed in Section 7.

4.2. Feast and famine

Taking the first derivative of Equation 1 for energy extraction yields:

$$P = 1/2 C_p \cdot A \cdot \rho \cdot V^3 \text{ Repeat Equation (1)}$$

First derivative of Equation 1:

$$\delta P / \delta V = 3(1/2 C_p \cdot A \cdot \rho) \cdot V^2 \quad (5)$$

Then the ratio

$$\delta P / P = 3 \delta V / V \quad (6)$$

The ratio in Equation 6 shows the effect of a mean annual wind speed change. In other words, **a 5% drop in windspeed leads to a 3x higher or 15% drop in power output**. At an 8 m/s mean wind speed for the North Sea sites where Germany is building wind farms, a drop of only 0,5 m/s (or 6,25%) in the annual mean wind speed causes a ~20% drop (3 x 6,25%) in electricity production, everything else being equal (this is also confirmed from actual data by Staffel and Green 2014). Measurements from Christiansen et al. 2022 show that 2-8% wind speed decreases occur from 3 to 50 km following the wind farms in the analysis.

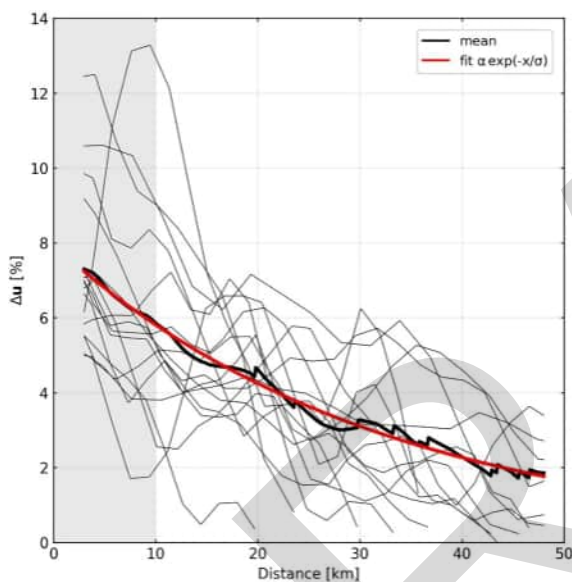


Figure 14: Offshore wind farm velocity deficit curves

Note: Δu = wind speed deficit. Graphs shows velocity deficit curves derived from SAR measurements for isolated wake cases at the 80 WT Global Tech wind farm in the German Bight (thin black lines). The thick black line indicates the average velocity deficit. The red curve corresponds to the best fit of the velocity deficit considering an exponential downstream wake recovery formulation.
Source: Christiansen et al. 2022, Fig. 2

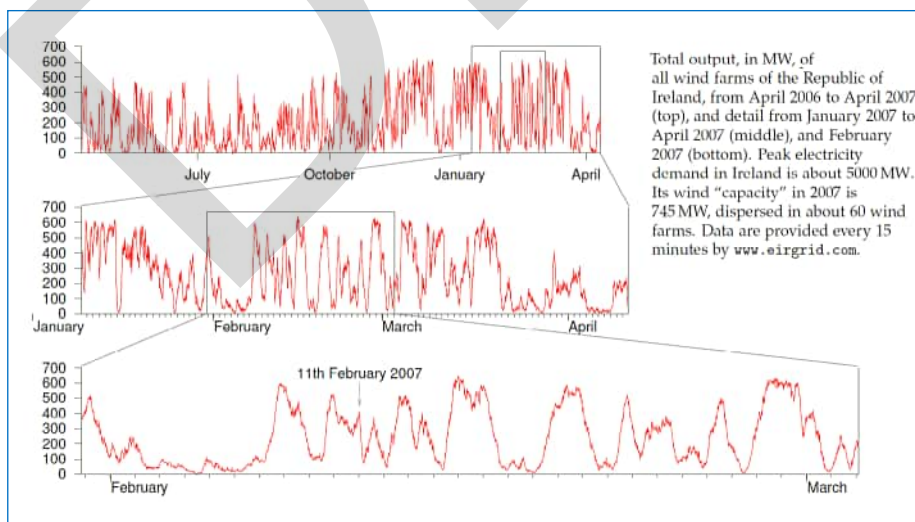


Figure 15: Annual to daily variability of wind over Ireland
Source: MacKay 2019, p187, chapter 26, based on EIRGRID 2022

A 0,5 m/sec wind speed change corresponds to a 6,25% decrease in wind speed which would persist to beyond 10 kilometers behind the nominal wind farm studied. This is equivalent to a permanent loss of ~20% output (Equation 6) from a second wind farm, even when spaced 10 km behind the first. This decrease can be ameliorated by increasing the space between wind farms which in turn limits the number of wind farms that can be placed in an available area. A red flag has recently been raised by the NAO studying potential wind speed variations that are coupled to a longer term ocean oscillation (Anemos Jacob 2018). This effect needs further study since it would impact wind farm size in a manner not included here.

4.3. The short-term fluctuations in wind

The annual peak-to-average power demand ratio (PA) is not yet a sufficient measure of the dynamic grid demands made on a wind (or PV) system. The erratic nature, plus seasonal and annual variations of the Danish onshore and offshore wind output data (Energy Numbers 2019) are plotted in Figure 12 where Danish and German data shows

1. that more than four times as much energy is produced at the winter peak, compared with the summer minimum,
2. the annual and multiyear output varies by at least 20%, and
3. offshore and onshore winds mimic each other closely.

These observations are consistent with our physical analysis discussed herein and were discussed for PV in Schernikau and Smith 2021. The enhanced wintertime output is favourable in that increased German energy demand in winter may be more easily met, but German energy demand falls by only 20% in summer. It is the summer power demand that determines the required number and size of WTs in Germany's wind farm fleet. On the other hand, if a high winter output could be stored as "green" hydrogen or through other means, then summertime energy demand could be partially met from electricity produced during the winter as part of a long-term backup capability. This capability, however, does not presently exist. Future H_2 production, with over 60% energy loss without counting for storage or transport losses would be in high demand by the many "renewable" applications that require storage.

Due to the effects of wind variation embodied in Equation 6, the average output of wind farms is deceptive. Wind farm energy production suffers from the large fluctuations derived in Section 4.1. Wind turbine output is erratic but highly correlated across very large regions.

The Irish wind data (EIRGRID 2022) in Figure 15 shows that wind short term variability (10 seconds to weekly) is dramatic. During the two-year period plotted, the erratic nature of wind caused 124 dropouts for Ireland. Wind output fell from over 1.200 MW to 20 MW, as metered by the National Grid. This occurred on an average of once every 6,4 days for just under 5 hours. The four highest peak power demand times coincided with a low wind output event, a "coincidence" often considered to be "highly unlikely". The Irish data show that a backup equal to the total wind farm output must be "on call" at all times. The alternative is to shed the entire load, or suffer grid collapse, as pointed out by MacKay 2009.

This is not just an Irish issue as was demonstrated during the Texas' February 2021 grid collapse (Austin American Statesman 2021) and as seen repeatedly in Australia (Stopthese things 2016).

The highly correlated speed of wind over Europe (Figure 9) ensures that dropouts will occur across Northern Europe at nearly the same time. Therefore, Germany must possess sufficient backup to bridge the gaps or endure the absence of electricity for the duration of weeklong dropouts as illustrated again during the 2-week wind lull in April/May 2022 (Figure 13).

4.4. The summer-winter conundrum

For July 2020, a typical German summer month (Figure 16) shows that most of the wind electrical power was produced in less than one-half of July, while little power was produced for the remainder of the month. Over two weeks of backup were met by base power which is scheduled to be reduced substantially (see Germany's coal and nuclear exit). Without several weeks of backup, German power demands cannot be met during frequent summer conditions of low wind. For half of the month, nearly all electricity must be supplied from a robust backup or an alternate energy resource, to be specified.

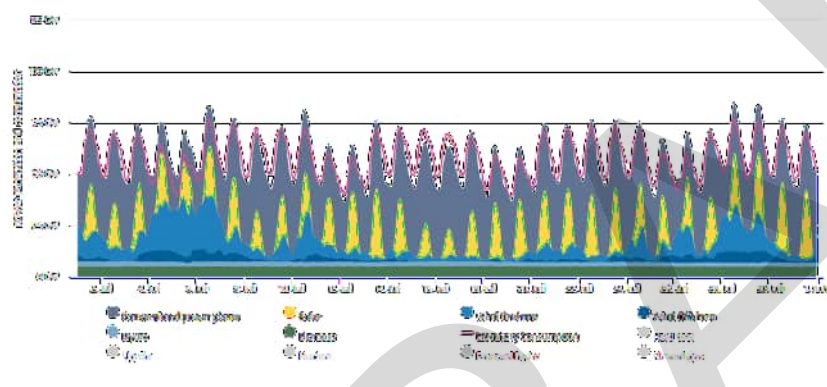


Figure 16: German power demand for July 2020

Note: Grey shows conventional electricity sources, such as coal, gas, and nuclear
Source: Agora 2022b

The data above shows, simply, that the energy system cannot be balanced without sufficient backup power or storage systems. In principle, backup is provided by pumped hydro, natural gas, coal, or nuclear thermal power plants. Under the German energy transition to "Net-Zero", by 2050 (now by 2035, CleanEnergyWire, 2022c.), pumped hydro is required and specified to increase dramatically, by as much as 3 TWh (WaterPowerMag 2013), while base power sources are to be eliminated. Since 2009, pumped hydro backup has, however, decreased by 10% (Statista 2022a) rather than increasing as planned. Since backup is required to be "carbon neutral", "green" H_2 is often suggested as the backup of the future. Industrial scale "green" H_2 does not exist and the maximum size of pumped hydro for Germany is at least an order of magnitude too small to provide the backup required as defined below. Additionally, EU climate chief Frans Timmermans also confirmed "Europe Is Never Going to Be Capable of Producing Its Own Hydrogen in Sufficient Quantities" (Collins 2022).

One of the most important realities of the German renewable electrical power system is found in Figure 11 and Figure 16. It is the transition from photovoltaic power in summer to wind power in winter. The wind and PV systems are highly seasonal in energy production. Each power source must be large enough to supply the bulk (80% or more) of the electrical energy during its favorable half-year. As a further consequence, a greatly expanded transmission infrastructure is required since most electricity must be shipped north in summer and south in winter. The grid system must use enhanced control

mechanisms to balance the grid with the resulting increased threat of cyber-attacks (see the Ukraine cyber-attack and electricity crisis during 2017 from the book Sandworm: A New Era of Cyberwar and the Hunt for the Kremlin's Most Dangerous Hackers by Greenberg 2019) or malfunctions.

The wind and PV are seasonally anti-correlated but not in shorter time periods. The expectation that an anti-correlated wind and PV would make these power sources mutually supportive is not supported by the data, and simply by the fact that at night it is always dark. Clear skies and high winds are weakly anti-correlated (Bett and Thornton 2016 and Miglietta et al. 2016). The German renewable energy system requires both: PV parks and wind farm systems, plus a long-term backup or storage system. From the data above, each system must be capable of practically meeting the total German power demand during its season. The backup must be capable of replacing the total power demand for time periods of at least one month to bridge the gaps in wind and PV energy production. Further, the differential in PV and wind resources must be balanced between winter and summer. The first difficulty is the physical size of the necessary wind and PV facilities, while the second difficulty is what the nature of the backup or storage will be.

The long-term backup solution to bridge low wind periods for a one month minimum, plus balancing the winter-summer differential in PV and wind resources, with a dynamic reserve would be nominally 12% of the annual electricity consumption, or 62 TWh. **A 60+ TWh backup remains entirely unrealistic at present and would require raw materials and energy to build and maintain that are beyond realistic world capabilities** (Schernikau and Smith 2021 and Schernikau et al. 2022).

Further, the observed four to five-year span with an average 20% deficit seen in the Danish and German wind farms requires a means to bridge multi-year deficits in power production. At present, there is

no solution for yearly, much less, multiyear deficits of 20% or more. The Danish and German wind farm output variations year over year exceed 20%. Germany just experienced a 13% wind power deficit for the entire year of 2021, in spite of wind farm size growth (EU JRC 2018). Based on the wind power extraction analysis in Section 4.2, a small decrease in the annually averaged wind speed causes a debilitating effect on power production which cannot occur if grid electrical sufficiency and stability is to be achieved.

The weak anti-correlation of "PV + wind" prevents an easy resolution of the grid stability issue. At the same time, it appears obvious from Figure 16: German power demand for July 2020 that PV output matches the diurnal variations of power demand better than wind, Schernikau and Smith 2021. Using PV to maximum advantage then suggests sizing wind farms to meet the peak winter demands and PV parks to meet the peak summer demands so that PV + wind provides the bulk of total energy requirements. PV parks still require a diurnal backup as defined by Schernikau and Smith 2021, along with an equal power capacity long duration backup. **The solution would effectively be three separate, but nearly equal power systems for Germany – wind, photovoltaic, plus a long and short-term backup and/or storage.** The nature of the long-term storage is not yet known. If, and only if, the renewable energy system matches the power/energy demand reliably will replacement of base power with renewable power be a success.

Configured as above, there would be a highly variable, but at times, high excess output from PV and wind. Since the entire power grid must be balanced, the excess output could be used for pumped hydro as planned, or to produce "green" hydrogen via electrolysis.

H₂, in principle, could be stored on site and converted to electricity via fuel cells on demand or used as vehicular fuel for autos, heavy trucks, and airplane travel if a suitable carrier medium is developed.

The use of H₂ in transport is an important research issue. We have considered the replacement of electrical power as consumed in Germany today. Creation of “green” H₂ to meet both backup and transport more than doubles the size of the required PV and wind energy systems since only the excess electricity production can contribute to backup. Known losses during long-term battery energy storage and low energy storage capacity render batteries useless as backup (Schernikau and Smith 2021). Battery energy storage for electric vehicles may in theory be displaced by fuel cells and “green” H₂. However, “green” H₂ remains an economically and energetically inefficient storage and transport energy carrier (Schernikau et al. 2022) and is considered the “champagne of energy carriers” by German “green” energy transition supporter Prof. Kemfert (Kemfert 2021). However, transporting H₂ as electricity, even with attendant losses, is still today’s best option, i.e., on-site storage of H₂, conversion back to electricity via fuel-cell and transmission to consumers. Pumped storage could supply a maximum of 10% of the backup for Germany, if fully built out (WaterPowerMag 2013).

5. Simple check: why wind plus PV cannot power Germany at today’s energy intensity

Let’s set aside the detailed analysis for a moment.

The total primary energy consumption of Germany, according to Our World in Data 2022 is 3.800 TWh or 425 GW annually. The total 425 GW of power divided by the total land area of Germany, 357.000 km² specifies the delivered primary energy demand density of ~1,2 MW/km².

This primary energy demand density may be marginally consistent with the conversion of all incoming solar power for Germany via wind and/or PV. We established in Section 4.1 that total wind farm area required to replace the present average German electricity – accounting for required reserves, aging, but not for backup, etc. – would be in excess of 350.000 km² if all is offshore, and more than 550.000 km² if all is onshore, or a combination thereof. The 7.500 km² of land area (2%) plus 7.000 km² in the German Bight assigned by diverse German agencies and think tanks to supply renewable power to Germany can produce ~36 GW of electricity delivered to the customer. This delivered power is far too small and too erratic, as we have detailed above. This simple disparity illustrates the dilemma perfectly.

The MacKay 2009 intentionally optimistic wind power extraction estimate of 2 and 3 MW/km² yields essentially the same result: there is too little space available in Germany. Our detailed analysis gives the same result: the German land mass and available sea area of Germany must contain one 10 MW nameplate capacity WT for every 5 km². The energy density of the wind turbines then matches the continuous power extraction of 2 MW/km² which MacKay 2009 assumed to be available from the atmospheric wind field. The German wind resource declines from the North to the South. The Southern part of Germany is poorly suited to wind farms (MenschNatur 2019). Available and useful space establishes the nominal power extraction from a given wind farm onshore and offshore. Since energy extraction and restoration rate ERR limits the extraction of wind energy from large scale wind farms, **the concept of 100% renewable wind derived power for Germany essentially requires the entire country to be covered with wind turbines.**

At the same time, the data (Schernikau and Smith 2021) show that PV yields no more than 5 MW/km² in Germany. Then, the space between the wind turbines in the southern half of Germany could be

covered with PV parks to match, approximately, the summer-winter power dichotomy described above. Finally, **a separate but equivalent backup power source with a duration of at least one-month (more realistically 2 months) is required for bridging the inevitable dropouts.** See Section 8 for the backup discussion.

Without such a backup, the renewable energy system will create a life in Germany that is intolerable on many levels. Needless to say, any country with only variable renewable energy will be hamstrung by the frequent necessity to curtail energy consumption by load shedding since dispatchable power is no longer available. The only reason load shedding has been limited to date is the presence of a large base power component as demonstrated by Germany’s unchanged installed fossil-fueled power capacity during the past 20 years (Schernikau et al. 2022). That capability is scheduled to largely disappear under “Net-Zero”. The country with only “renewable” energy will be at a fundamental disadvantage to any country with dispatchable power energy on demand.

6. Ecological and climate hazards associated with wind farms

Undisputedly, wind farms have some undesired ecological and climatic impacts on our environment. How significant or insignificant these hazards are, is discussed in the following sections.

6.1. Birds and bats

Activists and “renewable energy” advocates in Germany are demanding that the competing interests of ecology to be made subsidiary to desired deployment of “renewable” wind and solar energy sites. This may be due to the recognition that the allocated areas of Germany are far too small to accommodate the wind and PV required to meet Germany’s power requirements. Complying with that demand may set the stage to place sustainability of the ecology at risk, including effects far beyond Germany. Bird, bat, and insect population issues are trivialized by wind power interests, but in a fully developed wind system, these concerns are anything but trivial. Here, we extrapolate the present data to the planned variable renewable energy development.

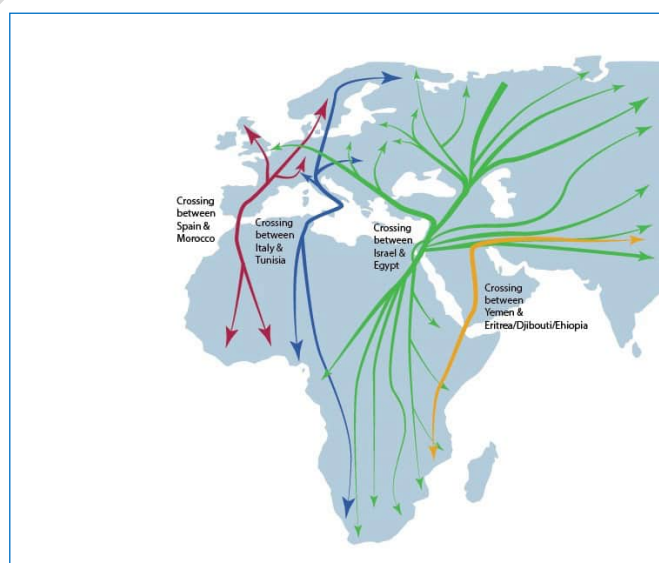


Figure 17: Bird flyways through Europe
Source: Wysinfo 2022

The future can be seen in Figure 13. The planned high density wind turbine farms, over land and sea, using the next generation of larger and taller WTs, blanket migratory bird flyways. We discuss only migratory birds here, but the situation is similar for non-migratory birds.

Migratory birds fly right through the wind farms onshore and offshore. Studies, such as Walston, et al. 2016, show that the present small wind farms destroy at least 100.000 birds annually. The data also show that most kills are not observed since birds die outside the limited search area and usually the carcass is entirely eaten. Large raptors are especially vulnerable since their numbers are small. 150 dead Golden Eagles, for example, were counted on site, but no one knows how many died off site since carcasses do not last long before scavenging occurs. See also Collopy et al. 2017, Devitt et al. 2020, and WashingtonPost 2022 on ecological effects of wind and solar.

Bird kills from tall buildings and from cats in urban areas are known to be large, but neither buildings nor cats are killing top predators such as the Red Kite in Germany. Adding another rapidly growing death source due to wind turbines to already large losses may tip the balance from survival to extinction for selected bird species. Remember, growing wind and PV projects will impact the ecological systems more seriously with every year (Devitt et al. 2020). The German government has, however, taken action to ensure that building wind farms are granted complete priority over bird extinction issues (Clean Energy Wire 2022b). Sovacool 2012 found that nuclear and fossil fuel power plants vastly exceeded the bird kills for wind, solar, and PV power plants. This cannot be considered a serious study since the overwhelming bird kills are ascribed to “climate change” which Sovacool could not quantify.

Bats, on the other hand, apparently do not need to collide with a blade. Their lungs are crushed and then explode by the rapid pressure changes before and behind wind turbine rotors (UW Conservation 2014, NewScientist 2008). The numbers of bat deaths were twice the number of bird deaths in Spain (ClimateScience 2022).

6.2. Insect mortality and magnetic fields

Many organizations are concerned with birds and bats, but what about insects? Just as in “saving the whales”, it is the lesser species near the base of the food web which are often not noticed despite great potential losses. The greatest harm to the ecosystem, and to humans, can occur due to those insect losses (Trieb 2018). Insects migrate to breed and to find favorable terrain. Trieb 2018 estimated from research data the insect fatalities for Germany alone. The researcher uses an estimate from Sandia data on bug residues from actual wind turbines, to arrive at a 5% collision rate. The quoted study estimates 25 trillion killed insects. The analysis also concluded that WT **efficiency losses due to insect residue on rotors would reach 50%**. This effect may also contribute to the ‘unknown’ reason for the measured deficit of 27% already mentioned above (Germer and Kleidon 2019).

A further ecological question is what effects the varying magnetic fields surrounding larger grid-scale wind farms might have? The fields are supposed to pose no human risk (McCallum et al. 2014), however, migrating birds can “see” magnetic field lines and are thought to use them for guidance during migrations. Rotating and twisted magnetic fields are generated by the immense permanent high field strength magnets. These have been measured and exceed the Earth magnetic field strength out to distances of 100-200 meters surrounding each wind turbine. This is an entirely new situation; an area of hundreds of km² with tangled magnetic vortices. Could such magnetic fields mislead birds into wind farms? No one knows.

New studies also found that infrasound impacts human health. Nguyen et al. 2021 found that wind turbines can be harmful to health (see also France-Bleu 2021). Professors Roos and Vahl 2021 studied infrasound of wind turbines and also found harmful

effects. Do these effects extend to animals grazing under wind turbines? Research is needed.

6.3. Climate consequences of wind, and PV

The global climate, like the ecological system, is sensitive to change. The best data imply that the Earth has warmed about at 0,70° C per century over the past 150 years (WMO JMA 2022). Humanity, realistically, could not have caused significant warming before ~1980, but, since the late 1970's, practically all warming is ascribed to human energy production and the climate forcing of CO₂ (Kellogg 1977). This assessment has not changed in 2022. The stated goal of many governments (IEA 2021a, CleanEnergyWire 2021) is to “decarbonize” the global energy system to stop global warming. To date, over US\$ 5 trillion has been spent to stop climate change (OhAiseadha et al. 2020). Germany, contributing about 2% to global GHG emissions, has been a leading nation in this effort.

“Net-Zero 2050” (IEA 2021b) is the plan to achieve decarbonization by creation of a global energy system composed of vast “renewable” facilities with a focus on wind and solar.

The long-term wind energy potential for Germany (Hoogvijk 2008) is calculated to be 39.000 TWh p.a., or 4,4 TW of electricity. This power corresponds to the output of 3,3 million 4 MW nameplate WTs operating at the 25% capacity factor noted in Section 2.5. That number is 100x the present German wind power fleet which so far occupies about 0,5% of Germany (Umweltbundesamt 2019, Naturschutz 2020). The required wind fleet would necessarily occupy most of Germany, as we have also calculated here. The climatological, as well as ecological consequences of even 10% of such a proposed wind fleet are significant if not extreme, yet >1 TW wind power for Germany is seriously proposed (Agora 2020, Naturschutz 2020) with similar plans globally.

Christiansen et al. 2022 discuss a new ecological impact. **Offshore wind farms slow the wind and create wake turbulence. Together, the changes affect the mixed layer in the oceans to depths of 100 m.** The net effect is to decrease Ekman transport in the mixed layer, reducing nutrient transport in these shallow, but highly biologically productive sea waters. Most biological productivity occurs in the mixed layer, or photic zone, the upper 100 meters of the ocean. This results in a decline in sea and avian life and fisheries in the affected regions.

The North Sea and Baltic Sea experience prevailing wind directions that establish the Ekman transport. If the ‘wind rose’ is altered and contains more turbulent kinetic energy due to the presence of large wind farms, then, the upward mixing of nutrients in the affected sea will decline. The effects of changes in wind speed, duration, and addition of turbulent kinetic energy is presently unknown and now being investigated (Austin American Statesman 2021). The speed and direction of prevailing winds determine the upward mixing of nutrients in the sea.

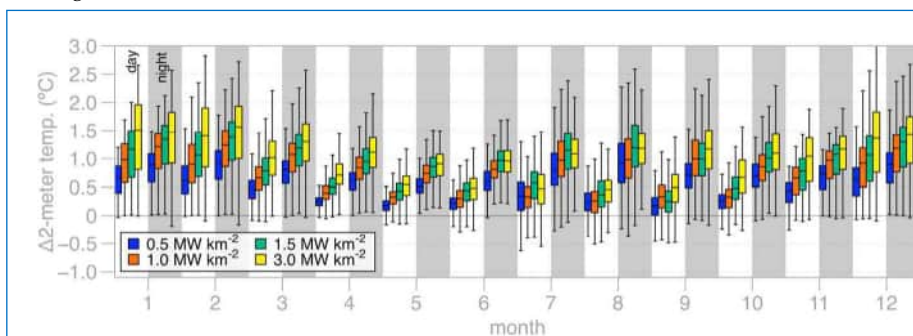


Figure 18: Warming impacts of large-scale wind farms

Note: Day and night 3-year monthly mean 2 m air temperature differences over the wind farm region between various turbine densities and the control simulation. Vertical line is 1.5-times the interquartile range and the box represents the 25th, 50th, and 75th percentiles
Source: Miller and Keith 2018, supplemental material, Figure S7

The effect of larger and larger offshore wind farms is highly concerning. Wind turbines may also induce warming downstream (Miller and Keith 2018, Science Daily 2018).

Adams and Keith 2013, and Fitch 2015 made measurements and / or modeled climate effects in large wind farms. Qualitatively, their results agree. Miller and Keith 2018 updated the analysis (Figure 18). “Large-scale US wind power would cause warming that would take roughly a century to offset” (Science Daily 2018). **Large-scale wind farms warm the climate.** Lu et al. 2020 have detailed global temperature rise and northward shift of the Intertropical Convergence Zone ITCZ caused by large-scale solar PV farms in the Sahara. Devitt et al. 2020 also demonstrated grid-scale solar PV induced warming. Full build-out to match power demand as demanded by “Net-Zero 2050” would likely raise global temperature by over a degree centigrade, negating the purported benefit of decarbonization. There are putative effects on cloudiness, on precipitation, and on stagnation of air masses, all of which lead to undesirable climate consequences. Stagnant air masses would, for example, create heat islands for each large wind farm, changing regional climate in presently unknown but possibly serious ways.

These consequences are in the near future, if wind farms reach the full scale envisioned by “Net-Zero 2050”. The models and data are consistent, but only the full experiment will prove the case, and then, it may be too late as untold US\$ trillions will have been spent. Effectively, we are committing to a scenario, not allowing an evolution.

6.4. Energy poverty due to wind and solar PV

Global energy poverty continued to increase in recent decades (IEA 2021c). Unfortunately, one cannot ignore the large and increasing number of human lives lost due to energy poverty in the developed world or due to slower fossil fuel adoption caused by reduced funding in the developing world. The use of “renewable” energy directly causes higher energy prices (Schernikau et al. 2022, Stopthesethings 2016). Reliable and affordable electricity supply is crucial for social and economic stability and growth which in turn leads to eradication of poverty. Unfortunately, variable renewables are neither reliable nor affordable at grid-scale. CNN wrote in Nov 2021 (CNN 2021): “... anti-poverty organizations and environmental campaigners have warned that millions of people across Europe may not be able to afford to heat their homes this winter ...”.

Energy prices have risen sharply as the putatively cheap “renewable” energy contribution has risen. Major countries with the highest percentage of variable renewable energy are those with the highest energy prices. Along with the growth of “renewable” energy, the rise of energy poverty has already cost 10s of thousands of lives in the West (Bloomberg 2022, CBN News 2022, Express 2014). If renewable energy is cheap and getting cheaper, as asserted; the high cost of energy in the leading country in the energy transition, Germany, is inexplicable. Facts speak for themselves. For a more detailed discussion on the full cost of electricity FCOE and energy returns eROI please refer to Schernikau et al. 2022 which details the energy economic reasons why “renewables” cause higher costs when employed at grid scale and why using the commonly used leveled cost of electricity LCOE is incorrect and misleads politicians and decision makers.

In addition to lives lost due to energy poverty, it is incorrect to assert that “renewable” energy is cost-free in human life. Forbes 2012 summarizes that biomass / biofuels cause more death from accidents than coal mined in the US, where mining safety is of high importance. As per Forbes 2012 and P. Scherrer Institute 1998, the nuclear replacement would cost many fewer lives than “renewables”, even before including the ecological effects we have outlined here.

6.5. Greenhouse gases and global warming

Neither global warming, its sources or impacts, nor the role that anthropogenic greenhouse gases may play is the subject of this paper. However, discussion of energy economics always assumes that CO₂, and more recently CH₄, dominate global warming. For this reason, both the costs and the benefits of CO₂ and CH₄ should be considered in any cost and benefit analysis of each hydrocarbon fuel, namely coal, natural gas, and oil versus “renewable” sources of power. The readers are invited to consider the general practice in Western Europe to couple intermittent wind and solar with natural gas (see new gas fired-power plants in Germany or the EU’s decision to put gas on the “green” list, Independent 2021b).

While disregarding the known benefits from CO₂, **Nobel Prize winner Prof. Nordhaus calculated a GDP damage of 2,8% in 2100 from global warming**, assuming his “optimal scenario” with 4,1°C warming since 1900 (Nordhaus 2018). For comparison, the UN announced in 2021 that their current climate trajectory to 2100 is in line with about 2,7°C warming from pre-industrial times (1850-1900), of which 1,1°C-1,2°C have already occurred (UNFCC 2021). The cause of global warming prior to 1980 is unknown, but since 1977 to date. Global warming is ascribed 100% to anthropogenic global warming, according to climate modelers (Kellogg, 1977, Schmidt, 2017). The source of warming prior to ~1980 is stipulated to have disappeared. Prof. Nordhaus, Nobel Prize winner for “Climate Economics” in 2018, estimates the GDP cost of global warming under different scenarios using his DICE model (the merits of using the GDP metric will not be elaborated in this paper). Suffice it to say that Prof. Nordhaus makes the following important statements confirming that **reduced use of fossil fuels will lead to reduced growth and therefore reduced wealth:**

- “... the revised DICE model shows more rapid growth of output in the baseline or “no-[climate]-policy” path compared to earlier DICE versions and most other models.”
- “... the international target for climate change with a limit of 2°C appears to be infeasible with reasonably accessible technologies even with very ambitious abatement strategies. This is due to the inertia of the climate system, of rapid projected economic growth in the near term, and of revisions in several elements of the model.”
- “A target of 2,5°C is technically feasible but would require extreme and virtually universal global policy measures in the near future.”

Prof. Nordhaus’ optimal DICE scenario which stipulates a peak in CO₂ emissions (not airborne CO₂^{eq}, which is currently below 50% of annual emission) around 2050 at ~40 Gt and a global warming of 4,1°C. This model uses the implausible IPCC RCP8.5 climate scenario (Pielke and Richie 2021). For comparison, 10% of GDP was lost after 3 years during the Great Depression. Lomborg 2020 and Kahn et al. 2021 basically confirm Nordhaus’ model calculations, with similar stipulations.

The potential effects of climatic changes, both positive and negative, cannot be discounted. **The benefits of increased CO₂ concentrations in the atmosphere because of its undisputed fertilization effects on plants are confirmed** by numerous peer-reviewed studies, a selection of which is detailed in Footnote 2. In addition to adjusting for CO₂ fertilization, the modeled economic impact of global warming – to be fair and complete – should be compared to the costs and impacts of prematurely forcing energy systems away from conventional fuels prior to having a truly sustainable energy solution, causing energy starvation as explained in Schernikau et al. 2022.

Carbon, oxygen, hydrogen, and nitrogen are the four most important elements for life. **Carbon dioxide is a key building block for all life on Earth as all plant life depends on CO₂, water, and solar radiation** for photosynthesis. In fact, atmospheric CO₂ is the sole

2. A list of selected peer-reviewed studies confirming benefits of increased CO₂ concentration in the atmosphere are summarized by Dr. Craig Idso at CO₂ Science ([link](#) & [link](#)).

source of carbon contained in plants, and therefore in human and animal bodies. The CO₂ concentration in the atmosphere increased by a little more than 0,01% or 100 ppm or over 30% in the past 100 years, apparently mainly due to combustion of carbon-rich oil, coal, and natural gas.

The release of additional CO₂ contributes to global climate warming both positively and negatively, for example, as a greenhouse gas and as the cause of very significant greening of our planet. NASA and the World Economic Forum confirm that elevated CO₂, slight warming, and precipitation increases contributed to the net greening of the Earth over past decades (NASA 2019, WEF 2019). The increase in the Leaf Area Index (LIA) and Vegetation Index due to CO₂ fertilization has been confirmed by numerous researchers. This greening is crucial in providing sufficient food to the growing population. The benefits have not been properly integrated into GHG policies. Zhu et al. 2016 point out that vegetation increased by about 14% from 1981 to 2014, of which about 70% is due to CO₂ fertilization. This growth equals an area twice as large as the USA. Deforestation counteracts CO₂ fertilization and needs to be further reduced, however, at a global scale, more biomass is added then lost from deforestation.

- ~0,4% core materials (primarily foam, plastic, and balsa wood).

In 2008, utilities and manufacturers installed more than 5.000 utility-scale wind turbines in the United States, requiring more than 1,1 million metric tons (Mt) of iron and steel, 920.000 m³ of concrete, 2,4 million steel bolts, and 43.000 km of reinforced steel rebar. WSJ Mills 2022 and USGS 2011 suggest that achieving the market penetration “renewable” goal of 20% by 2030 would require an average annual consumption of about 7 Mt of concrete, ~1,5 Mt of steel, ~300.000 tons of cast iron, ~40.000 tons of copper, and over 350 tons of the rare-earth element neodymium. These quantities are in addition to present consumption. Provision for growth in mining, processing, transportation, and utilization of the materials and commodities is not explicated in the plans. IEA 2021d and DEA 2015 confirm that “renewable” energy generation technology requires more raw materials than conventional energy technology (Figure 20).

The fabrication of wind turbine farms, PV parks, and essential infrastructure must be planned comprehensively (USGS 2011). **The quantities of materials and commodities, such as iron, concrete, copper, neodymium, balsa wood, manganese, lithium, aluminum, silver, silicon, plastics, ceramics, etc., must be available. Most importantly, also the energy (from conventional fuels) to mine, harvest, transport, and process and refine these materials cannot be discounted and is substantial.** In a modern world, it is curious that balsa wood is a critical component for wind turbine blades. Overharvesting of balsa has already depleted the tropical balsa forests, contributing to their potential extinction, if the exploitation continues and grows (Stoessel 2021). Alternate materials exist, laminated porous plastics, in particular, but these are more expensive and less suitable.

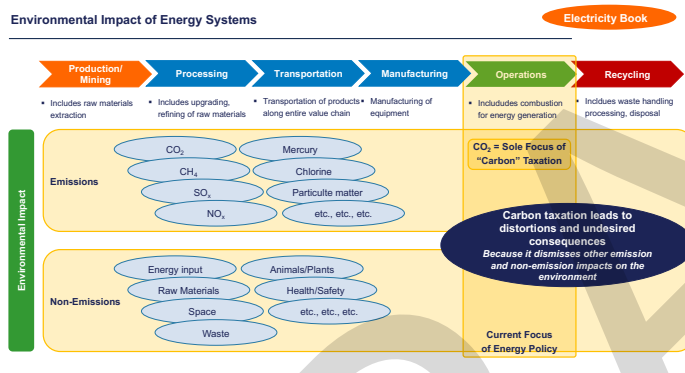


Figure 19: Environmental impact of energy systems – why carbon taxation leads to distortions and undesired consequences
Source: Schemnikau et al. 2022

In summary, our lives and energy systems have environmental effects, including the potential warming from anthropogenic greenhouse gases. However, higher CO₂ emissions such as those from fossil fuel combustion are beneficial for plant life. These undisputed facts also need to be considered in energy policy. The environmental effects from energy generation and consumption are however not limited to GHG as detailed herein and in Figure 19.

7. Commodity requirements

Our analysis shows that literally gigantic wind farms would be required to meet Germany's energy demands from wind alone. Consequently, there are far larger commodity requirements than generally acknowledged (WSJ Mills 2022).

A typical wind turbine is reported to contain by weight-% (USGS 2011):

- ~89% steel,
- ~6% fiberglass,
- ~1,6% copper,
- ~1,3% concrete (primarily cement, water, aggregates, and steel reinforcement),
- ~1,1% adhesives,
- ~0,8% aluminum, and

In response to the exponential increase in mining, fabrication, construction, and maintenance of wind farms and PV parks, the number of accidents and deaths will grow exponentially. Germany's intended installation of 1 TW of wind turbines will directly cost only a few German lives annually, but many more lives will be lost globally, due to the mining and processing of the vast quantities of needed commodities.

Figure 21 summarizes IRENA's view on cost of key materials per kW wind generation capacity. Be reminded that these materials displayed are not raw materials, but processed materials. It must be considered that China is the leading raw material processing country. China uses largely coal for the low-cost processing energy required and in case of solar panels relies partially on forced labor (Murphy and Elima 2021).

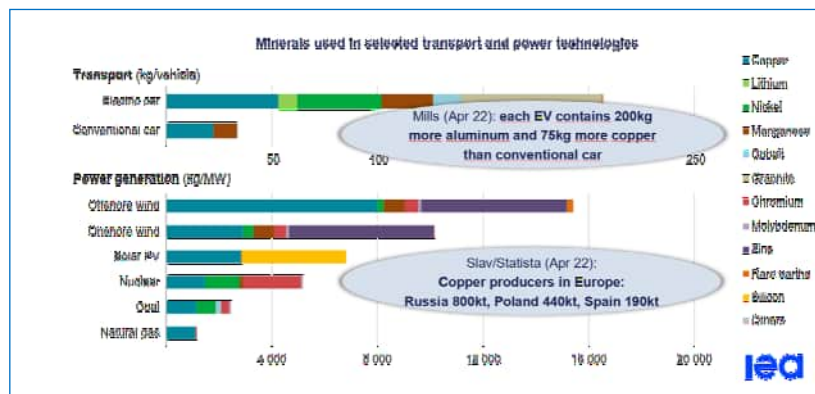


Figure 20: Comparing mineral needs for “renewable” technologies
Source: The Role of Critical Minerals in Clean Energy Transitions, IEA 2021d, p6

9. Conclusions

For the German “Energiewende” to replace fossil fuels successfully, we have demonstrated that a PV park and a wind farm must be paired and that each facility must have a power output equal to the peak demand plus the dynamic reserve. Remotely sited pairs of wind farms cannot succeed due to the high correlation of wind speed. We previously determined that a German PV facility must be greatly overbuilt (Schernikau and Smith 2021) and now we find that a wind energy facility also must be overbuilt by 2,2 times just to meet peak power plus dynamic reserve demands, not including seasonal variations nor enough to charge a backup system. The very large power transmission and conditioning infrastructure that is required for the fully variable renewable power system is far from being addressed. For example, the required computing and control components to manage the grid with power flowing from opposite parts of Germany between summer and winter are not analyzed yet. This situation is completely different from the former hydrocarbon or nuclear based power grid and presents enormous material and commodity demands.

Physics defines the limits on wind farm electricity production at scale, just as we found earlier for PV parks (Schernikau and Smith 2021). The known losses between variable “renewable” electricity production and the consumer must be included in any modeled “renewable” system. It is essential to supply 550 TWh of electricity, the current German electrical energy demand, reliably and on demand. Our back-of-envelope calculation using published data is straightforward and shows that wind power cannot plausibly grow to replace Germany’s present energy system for any division of the wind facility of 2050 between onshore and offshore. Even assuming the generous MacKay 2019 onshore and offshore power densities, available space is insufficient. This deficit is addressed by accepting a decrease in wind farms capacity factors, which, in turn, requires yet more wind turbines crowded into too small a space.

An acceptable replacement energy system for Germany must avoid frequent grid collapses. A PV plus wind system that meets the peak-to-average demand ratio and dynamic reserve (PA+DR) standard, but without backup fails in stability. The energy system requires backup or storage to bridge the wind and solar gaps. Backup is also essential for grid balancing. Overall, wind plus PV leads to a very complex grid with many US\$ billions required just for control systems and to avoid IT failure or cyber-attacks.

The “green” energy system must include long duration backup energy storage capable of meeting essentially 100% of the German energy demand for at least one month. Such a backup capability presently does not exist. Storing excess electricity as heat in molten salts as a component of PtHtP can work for short-term storage, 8-10 hours, but is inefficient and too limited for longer term storage demands. Even if the entire Norwegian hydroelectric facility were dedicated to backup for Europe, it is far too small. “Green” hydrogen has attention focused on it, but is still in a primitive stage of development and comes with inherent energy inefficiencies. The three “green” hydrogen “show-stoppers” are (1) production from inherently energy inefficient, excess variable “renewable” electricity, (2) storage and (3) transmission, none of which is a solved issue at grid-scale (Schernikau et al. 2022).

These considerations underscore an advantage of hydrocarbon fueled and nuclear thermal (HFNT) power plants. First, smaller transmission losses are incurred by HFNT power plants are normally sited near customers so ‘plant to customer distances’ are smaller, i.e., long undersea transmission cables are never required for any thermal plant. Next, “conditioning losses” are specific to wind farms and PV parks. Dispatchable base power from close-by thermal plants is less complicated to manage and losses are smaller. The calculation of the areas demanded by a wind + PV power system compared with

HFNT plants shows clearly, as MacKay 2009 warned: **Country-sized solar-wind power plants are required to meet present energy demands.**

High efficiency has always been considered a plus for “green” energy power plants. There is no Carnot cycle thermal inefficiency directly encountered in green electricity production. The efficiency of converting raw wind into electricity is between 10% and 30% (Section 2), but the wind is considered ‘free’. That is quite true. However, we have demonstrated here that wind is not an unlimited cornucopia; just as we demonstrated earlier the limitations of PV parks. The energy from renewable energy plants is paid for in space costs, materials costs due to massive hardware and infrastructure demands, and in control and backup costs. The thermal losses of HFNT plants are paid for in fuel costs. These losses can be reduced by co-generation, a readily available means to enhance HFNT power plant efficiency. HFNT plants, conveniently located near industrial and residential facilities, can utilize the HFNT waste heat. This raises the overall efficiency of HFNT USC plants to over 60% (PowerMag

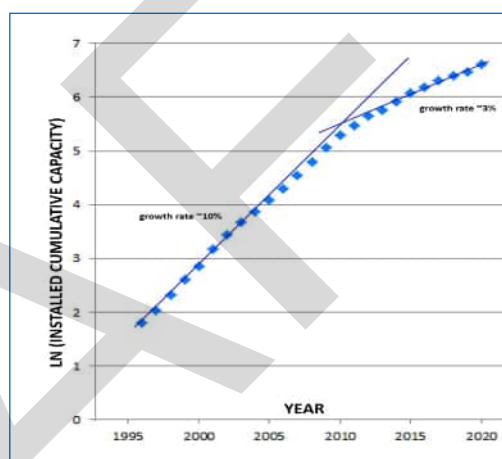


Figure 22: Installed capacity growth rate for wind turbines 1995 to 2020
Source: Statista 2022b, plotted from Excel

2018). Compared with the usual thermal efficiency of 30%, only half as many plants are required by doubling the efficiency.

Co-generation is not possible with variable “renewable” energy. We showed, in Section 4, that the at-plant power production must be tripled to meet the power demand at the customer. These conversion and conditioning losses are unique to wind and solar energy and are a cost. The efficiency of variable “renewable” energy delivered to the customer has a typical 10% loss in transit, just as thermal power plant electricity does. However, delivered “green” energy losses detailed in Section 4, when viewed from this perspective, show that USC thermal plants are more efficient, overall.

The annual installed capacity growth rate for wind turbines globally has declined from 10% between 1995 and 2010, to 3% between 2010 and 2020 (Figure 22). This slacking off of growth suggests that Germany and other countries are having difficulties maintaining an exponential expansion to reach “Net-Zero 2050” goals. Capacity factors of 11% and 24% for PV and wind, respectively, were achieved using the best areas of Germany. These will not be improved upon, especially if the anticipated crowding occurs. Thus, average capacity factors will reduce significantly.

Transmission and control infrastructure seriously lags behind demand. PrincetonNetZero2050 shows that nearly 1,1 x 106 Gigawatt-miles of high-tension transmission are required by 2050, equated to an 8% annual growth rate. UT Austin 2020 finds that transmission lines are growing at about 2%, or one-fourth the required growth, resulting in a shortfall of nearly a factor of four by 2050, a true disaster if the shortfall occurs.

This brings us to the bottom line of our analysis. The “Energie-wende” will leave much of Germany in thrall to variable “renewable” energy production, while, in contrast, hydrocarbon and nuclear energy production leave nearly all of Germany and its surrounding seas open for the enjoyment of life and preservation of the ecology. Conventional power plants allow one to keep one’s country for living purposes.

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List of Figures

Figure 1: Mean speed and distribution of the global wind resource	4
Figure 2: Wind speeds in Europe	4
Figure 3: Weibull wind speed distribution curve	5
Figure 4: Power-velocity curve of four existing wind turbines	5
Figure 5: 15 month average ocean vertical wind profile	5
Figure 6: Actual vs. expected wind farm output	6
Figure 7: Illustrating wake effect and energy rate of restoration (ERR)	7
Figure 8: Wind speeds and actual capacity factors and wind speeds	7
Figure 9: Correlation in 30-day wind speed to a grid point in Germany.	8
Figure 10: Monthly mean capacity factor decline for onshore wind farms	9
Figure 11: Electricity demand in Germany from mid Dec 2021 to mid Jan 2022	10
Figure 12: Danish and German wind output correlation 2003-2015	10

Figure 13: Germany's wind generation 25 April to 10 May 2022, during 2-week wind lull	10
Figure 14: Offshore wind farm velocity deficit curves	12
Figure 15: Annual to daily variability of wind over Ireland	12
Figure 16: German power demand for July 2020	13
Figure 17: Bird flyways through Europe	14
Figure 18: Warming impacts of large-scale wind farms	15
Figure 19: Environmental Impact of Energy Systems – Why Carbon Taxation Leads to Distortions and Undesired consequences	17
Figure 20: Comparing Mineral Needs for "Renewable" Technologies	17
Figure 21: Wind turbine materials costs by major material	18
Figure 22: Installed capacity growth rate for wind turbines 1995 to 2020	19