

Conclusions — with personal reflections

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Summary. — Global warming necessitates a replacement of traditional technologies based on fossil fuels. The number of options is rather limited. Renewable energies will play a dominant role in this process. Whereas biomass and hydro-electricity are limited, wind and photovoltaic power (PV) can be upscaled to large capacities. The technical side of CO₂-free technologies has been covered in the bulk of these proceedings. In this paper, we concentrate on the main characteristics of an electricity system based mostly on wind and PV power and the consequences of integrating intermittent technologies. Most practical examples are taken from Germany. The question whether nuclear power can be considered as clean electricity source supplementing renewable energies will be discussed. Nuclear power will still play a role in 2050 and beyond in and outside of Europe.

1. – Introduction

Climate threats enforce a replacement of traditional energy producing and consuming technologies. The Earth power balance changes predominantly because of the excessive use of fossil fuels by human beings. Therefore, decarbonisation of the economy will become the global mission of this century. But we do not know how 11 bn people on Earth

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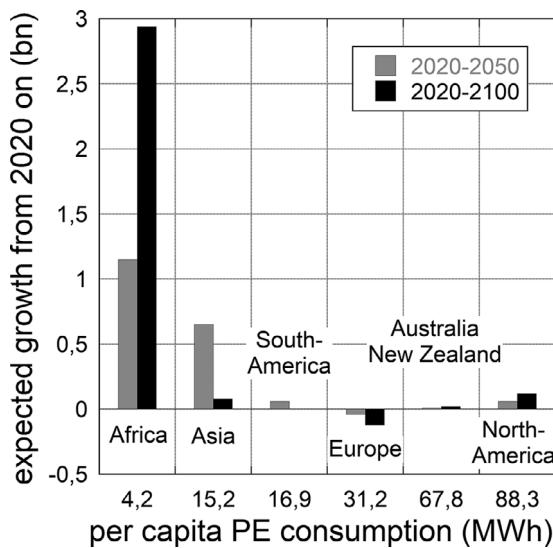


Fig. 1. – Expected population growth in different areas in two time periods —2020 to 2050 and 2020 to 2100 [1]— vs. *per capita* primary energy (PE) consumption of 2019 [2].

—expected by the United Nations for 2100— will organise themselves and co-exist. The primary problem is therefore the large population and its further growth. The energy problem is a direct corollary of overpopulation and therefore difficult to solve.

Figure 1 shows the expected growth of population in different areas of the world starting with 2020 *vs.* the present *per capita* primary energy consumption. Two cases are considered: in grey the expected growth up to 2050 and in black up to 2100. The continent whose population is expected to grow most is Africa, the one with the lowest *per capita* energy consumption. About 600 mill people in Africa do not have access to electricity now. As a contribution to fight global warming, energy saving cannot be expected from the African generations to come. The only serious options for Africa are clean energy supply technologies allowing an energy price, which moves fossil fuels from the market. The black continent needs urgently a green deal.

2. – Electricity as primary energy

There are only a few clean energy options available: to continue the use of fossil fuels on the basis of CCS technology (CCS stands for carbon capture and sequestration); fission with fast neutrons and breeder technology in the frame of the Generation-IV reactor concepts; nuclear fusion, and finally the different forms of renewable energies —biomass, geothermal power, hydro-electricity, maritime power (wave/tide/ocean currents), environmental heat in conjunction with heat pumps, onshore, offshore wind,

and solar energies in the form of photovoltaic (PV) and solar thermal power⁽¹⁾.

CCS is not supported in many countries and would not replace the need for transformation rather extend the time frame of it. Fission is often totally rejected even in countries with a long and successful history in science and technology and the demonstration of safe and efficient reactor operation for decades as it has been the case for Germany. Fusion will not contribute with a relevant share before the end of this century. Under these circumstances, only renewable energy forms remain. Therefore, their potential has to be discussed in detail. *E.g.*, the use of biomass is in conflict with nutrition and excessive production causes its own environmental problems. Hydro-, wave-, and geothermal power are limited to specific geographical conditions. Only wind and solar power can be scaled to large capacities and will, therefore, play a crucial role in the energy transformation process.

We conclude with the first major feature of the energy transition: electricity being produced largely by wind and PV power becomes the primary energy, serving all energy consuming sectors; chemical and thermal energies will be generated —not exclusively but mostly— from electricity.

3. – The epoch of the minerals

The second feature of the energy transition reflects the material needs of renewable energy systems (RES). The epoch of fossil fuels will be replaced by the one of the minerals. The consequence is that also the use of RES does not provide supply independence rather new dependences emerge. Figure 2 is taken from a very detailed recent report from IEA [3]. The critical minerals are listed here from copper to lithium to cobalt to the rare-earth minerals and others. Figure 2 shows the mineral use in the form of kg pro MW in case of power generation (fig. 2(a)) and demonstrates that renewable technologies need more of these minerals than conventional ones do. The case of transportation (fig. 2(b)) shows the demand in form of kg pro vehicle, again with a striking difference between electric and conventional cars. The large needs of copper (and aluminium) in electricity generation by wind and PV power are obvious because of low power density giving rise to distributed and complex networks. Zinc is needed to prevent corrosion as renewable energy technologies are located outside being exposed to the weather. Manganese is needed in steel production. The steel intensity (tons steel/MW [4]) of wind power is about a factor of four larger than that of nuclear power. Lithium, graphite and cobalt are used in Li-ion batteries, silicon in PV-panels. Rare-Earth minerals are needed for permanent magnets used in wind turbines (specifically in gearless systems) and electric cars.

The additional problem is that these minerals are available from a few countries only, less than in case of gas and oil, not to speak about abundant coal. The largest lithium

⁽¹⁾ Technical issues are presented and discussed in the proceedings of the *Joint EPS-SIF International School on Energy - Energy Innovation and Integration for a Clean Environment* (https://en.sif.it/courses/energy_school) and in the proceedings of previous schools and will not be discussed in this paper.

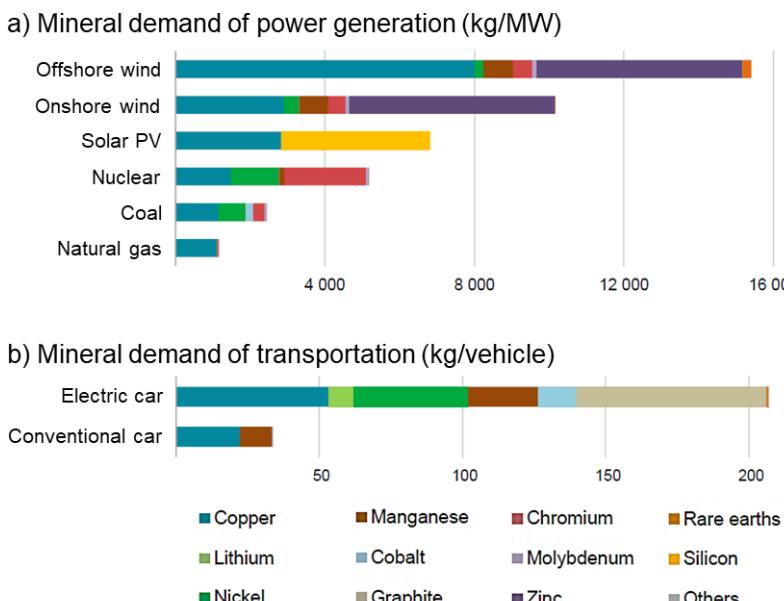


Fig. 2. – Mineral demand (a) of thermal and renewable power generation, and (b) of conventional and of electrical cars; the graph is reproduced from an IEA report [3], p. 26.

deposits are in Chile, followed by Australia, Argentina, China and USA [5]. Ganfeng lithium from China is the largest lithium miner in the world [6]. Tianqi Lithium of China controls nearly half of the world's production of lithium [3]. In addition, the processing technologies for these minerals are restricted to even less countries. Nearly 90% of the rare-earth minerals are said to be processed in China [7]. An additional problem is that the quality of mined minerals continuously degrades so that more energy and water (and money) is necessary for extracting a unit. On the other hand, mining of critical minerals has to be accelerated to meet the generally planned expansion of wind and PV power and of electric cars. *E.g.*, the demand of lithium for batteries is expected to grow by a factor of 40 between 2020 and 2040 [3]. Therefore, the energy transition needs to be backed by another transition in the way rare materials (and other commodities) are handled. Recycling will be a topic which will follow the process of decarbonisation and it is a wide field for research. Also, the notion of “sustainability” has to be expanded and applied to all technologies and used raw materials in a decarbonised economy. In a strict sense, only technologies whose realisation and operation are based on circular processes can be considered sustainable.

4. – Intermittent renewable energy systems

The work horses of the energy transition toward a comprehensive decarbonisation are wind and PV power. They are supplemented by sources with limited potential like

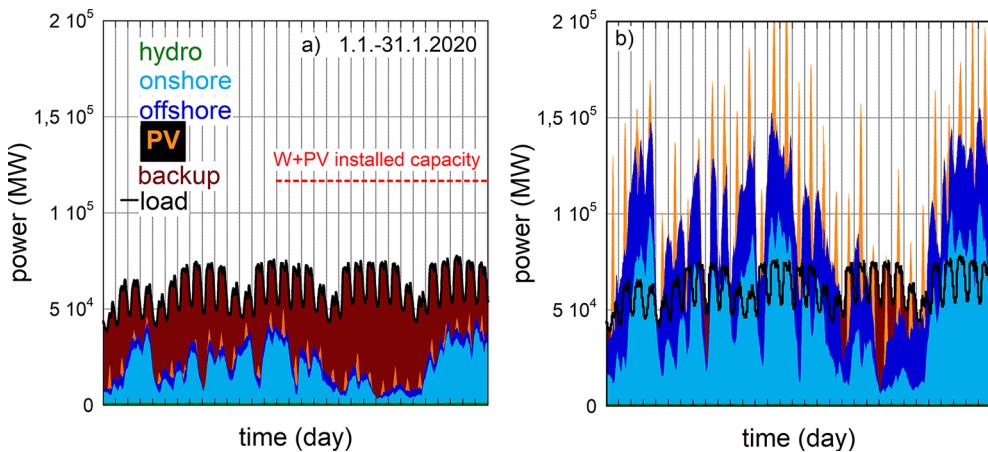


Fig. 3. – Power of renewable energy (RES) and thermal backup systems (a) for January 2020, and (b) up scaled to the production in 2045 according to the installations as suggested by “AGORA Energiewende” [9] with the following specification: onshore = 145 GW, offshore = 70 GW and photovoltaic power = 385 GW. The black curve represents the load of 2020 which has been left unchanged up to 2045 (alternative loads are discussed later in the text). For 2020, the installed intermittent renewable (iRE) power of 116 GW is indicated as dashed red line in fig. 3(a); for 2045, it is expected to be 600 GW [10].

hydro-electricity or energy forms partly needed for other sectors like biomass for aviation or heavy-duty mobility. The mix of renewable energies will vary strongly from country to country reflecting the prevailing natural conditions. Electricity from wind and PV installations will not only serve the electricity use proper but also contribute to meet the energy needs in other energy sectors like low temperature heat for buildings or high-temperature process heat for industry. Extended experience with the transformation exists already in case of electric cars introducing electricity into individual mobility. Because of the dominant role of electricity and the importance of wind and PV power in a future generation mix, it is necessary to discuss with some detail the characteristics of a supply system based predominantly on these two technologies.

4.1. Consequences of intermittency . – Wind and PV power have two characteristic features: variable power generation depending on the local weather conditions and low power density. First, we discuss the intermittent nature of wind and PV power [8]. In case of PV, there are short term —day/night— and seasonal variations. Figure 3(a) shows an example from January 2020 of Germany. Most examples in this paper are taken from Germany, which can be seen as a laboratory for the use of renewable energies in a still highly industrialised environment⁽²⁾. To a large extent, the German experience

⁽²⁾ Most data in this paper are obtained from the data banks of IEA (<https://www.iea.org/data-and-statistics>) and Entso-e (<https://www.entsoe.eu/data/>).

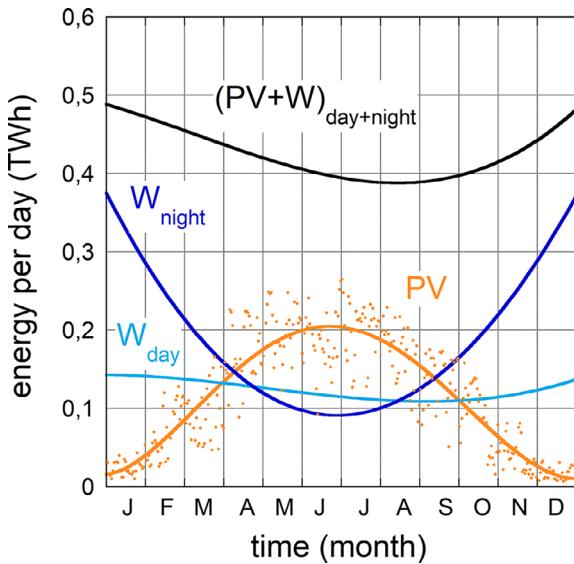


Fig. 4. – Daily energy generation by wind and PV power through the year 2018. For PV, the actual data points are shown along with a polynomial fit to guide the eye. For wind power and the sum of wind and PV, only the fits are given to simplify the diagram. For wind, day and night generations are separately shown. Definition: a day starts or ends when PV has reached 5% of peak power of this day (see main text).

can be transferred to other EU countries. The black curve in fig. 3(a) represents the load and it shows the day-to-day variation and the drop in consumption during the weekends. Plotted are also wind and PV power, with PV represented by the small orange needles sitting on top of blue onshore and offshore wind traces. PV is not very effective in winter. Wind and PV power capacities add up to 116 GW (end of 2020), shown as horizontal dotted line in fig. 3(a) being much above the maximal load of ~ 80 GW. In spite of the high installed capacity, wind and PV power cover only a fraction of the demand in January 2020. The gap is filled by backup power (brown) at present mostly by gas, coal and nuclear power.

In case of intermittent generation, there is electricity with two qualities: from wind and PV one has to take what one gets whereas the controlled backup electricity is dispatchable power which is added to exactly meet the load for every moment. The intermittent production necessitates a backup system, which —at a later stage— can be replaced by storage, producing clean secondary electricity. Storage will be discussed in sect. 5·3.

Figure 4 shows the daily electricity from wind and PV generation through the year 2018 highlighting the seasonal variation of renewable energy production. In case of PV, the daily energy values are plotted together with a polynomial fit to the data to guide the eye. In the other cases, only the fits are shown for clarity. The main purpose of

this diagram is to demonstrate the availability of wind power during and outside PV production. Therefore, the night is defined here when PV power is below 5% of the peak PV power of that day. The drop of PV energy toward the winter months is, of course, the consequence of lower radiation levels and shorter days (and possible snow coverage of PV panels).

PV electricity in January and December 2018 is about 11% of the one in July and August. In these periods, electricity supply from iRE is dominated by wind power. Average wind generation during the day is rather constant throughout the year (with the definition of day and night as used here) whereas wind during the night shows a strong increase toward the winter months. In spite of strong PV generation in summer, the total iRE production maximises in winter (black curve in fig. 4). This seasonal behaviour agrees with the seasonal variation of the demand in most European countries at least as long as global warming does not enforce widespread use of air conditioning in summer. Average electricity generation is larger during the day in summer and during the night in winter. It can be expected that the resulting electricity price variation will have a strong impact on user response (*e.g.*, loading car batteries in summer favourably during the day and in winter during the night).

In the transition period of the energy transition, the continuously operating RES—hydropower and biomass—are available along with growing PV and wind power supplemented by a backup system. It is generally expected that backup will finally be replaced by storage. The grid has to accommodate systems delivering several 100 GW power, feeding in at different voltage levels, being partly decentralised like onshore wind and PV power but possibly also with strongly centralised components like offshore wind. The save distribution of power from sources to sinks will be a major technical challenge. The complexity of such a supply system is further increased because PV power at a level of several 100 GW (*e.g.*, in case of Germany) leads to dramatic dynamics during sunrise and a few hours later during sunset and has the additional feature to basically drop out in the winter months. The dominant use of iRE necessitates therefore three critical components: wind and PV installations, a powerful and “smart” grid providing all necessary system services and a backup/storage system to generate secondary electricity. The visions of a distributed power system with prosumers adopting simultaneously the role of sources and sinks and which are seen as major market participants seems to be an idealistic view of the future supply reality.

4.2. Low power density of iRE and national generation potentials. – In this section, we will address the issue of low power density of iRE which will lead us to address national installation potentials. The identification of the actual potential for wind and PV installations is not a scientific rather a political issue. Non-scientific considerations play a decisive role like the conflict between wind farms and the protection of nature and habitats or the one between PV parks and agriculture. For the purpose of this paper, we select the proposed capacities AGORA has defined for Germany for 2045, when Germany is supposed to reach the net-zero CO₂ emission status. “AGORA Energiewende” [9] is a so-called think tank dealing mostly with the “Energiewende” of Germany. The AGORA

paper from 2021 [10] is one of the most recent publications on this topic. AGORA suggests 145 GW onshore, 70 GW offshore, and 385 GW PV power, in total 600 GW for Germany. Up to now, the maximal load is about 80 GW; at the end of 2021, 122 GW wind and PV power have been installed.

In fig. 3(b), the January 2020 data shown in fig. 3(a) are extrapolated to 2045 on the basis of AGORA's installation figures. The reference load profile assumed in this graph is the one of 2020, which is unrealistic for 2045 but will not change the conclusions drawn in his paper. Even at 600 GW, there is the need of backup at substantial power. In spite of 385 GW installed power, the PV contribution is still very small in winter. In addition, substantial surplus is produced, which will be conceptionally used to fill storage and replace the backup and/or to produce, *e.g.*, hydrogen to serve other energy sectors. Therefore, the energy transition falls into two periods: 1) the build-up period where backup is needed —preferably in a technology with low or no CO₂ emissions⁽³⁾— and 2) the final state of net zero-CO₂ emissions using clean surplus and secondary electricity from clean storage technologies.

4·3. Full-load-hours and capacity factors. — On the basis of well-defined national potentials of wind and PV powers, the annual electricity generation E can be calculated using full-load-hour (flh) or capacity factor (C) values:

$$\begin{aligned} E &= flh^{W_{on}} \times P_{W_{on}} + flh^{W_{off}} \times P_{W_{off}} + flh^{PV} \times P_{PV} \\ &= 8760 \times (C^{W_{on}} \times P_{W_{on}} + C^{W_{off}} \times P_{W_{off}} + C^{PV} \times P_{PV}) . \end{aligned}$$

flh and C depend on the weather conditions during a year and on the technical status of the employed generation technologies. This is of specific importance for new wind turbines, which reach the market with continuously increasing power both for onshore and offshore applications.

In the prediction of future iRE electricity generation, flh and C play an important role, with the complexity to anticipate the technological progress. Optimistic forecasts often ignore that specifically for wind generation the high-yield locations are already occupied and less favourable sites have to be selected in the future, that larger rotor areas are needed to obtain larger capacity factors [11] enforcing larger distances between wind turbines and that the interference of wind mills in extended wind farms cause flh and C to drop [12]. A natural power limitation for onshore wind is given by the logistics to transport the large rotor blades to the desired assembly sites.

Figure 5 compares the flh -values of the three iRE technologies and the general growth and annual variation of flh -values for wind and PV power over the years. flh of PV averaged over several years is about 55% of that of onshore wind, which itself is 52% of that of offshore wind. The lines in fig. 5 are linear fits to the data. The numbers on the

⁽³⁾ The concept in Germany is to use gas as backup. The recent steep price rise of gas and the supply security of Russian gas as a consequence of the Russian-Ukrainian war jeopardize this strategy.

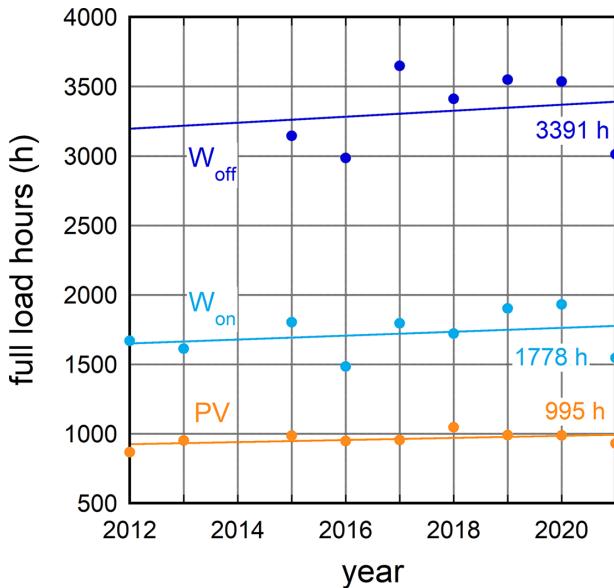


Fig. 5. – Development of full-load hours from 2012 (in case of offshore wind, W_{off} , from 2015) to 2021 for the three iRE technologies, onshore, W_{on} , offshore wind, W_{off} , and photovoltaic power, PV. The lines are linear fits to the data. The numbers on the right side represent the flh -values of 2021 as obtained from the fit-lines.

right side represent the flh -values of 2021 as obtained from the fit-lines. For all three technologies, flh slightly increases with time. *E.g.*, for onshore wind, flh increases by 14 hours per year in the average. The trend is small compared to annual variations *e.g.*, from 2016 to 2017, or 2020 to 2021. An increase of flh -values could be expected because the average turbine power of all onshore wind installations in Germany increased from 2012 to 2021 from 1.3 to 1.9 MW. Nevertheless, there is no basis for extreme expectations by selecting overly optimistic flh -values in simulation studies as one can often find in the literature.

5. – Simulation studies

5.1. Electricity generation. – Figure 6 shows the results of model studies on the basis of 2019 generation and consumption data. Basis are load, wind and PV power data tabulated with 15 min time resolution [13]. In the simulations, electricity generation is exclusively by hydro power at an unchanged level and by iRE —wind and PV power— upscaled to replace fossil and nuclear generation. Biomass is not considered though today typically 45 TWh electricity are generated by biogas. We assume that biogas is used for more critical applications in aviation or heavy-duty transportation.

In the first step of the simulations, the annual load L_a agrees with the present net electricity consumption of Germany: $L_a = 520$ TWh. The temporal course of the load profile

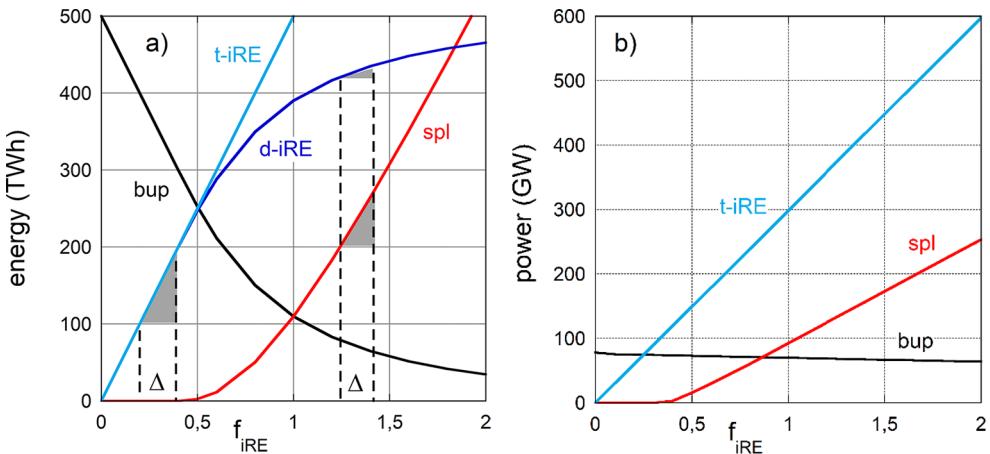


Fig. 6. – (a) Energy generation *vs.* the normalised intermittent iRE share, $f_{iRE} = E_{W+PV}/T_a$, for the conditions of 2019. This relation is shown for the total iRE generation, (t-iRE), the directly usable iRE share, (d-iRE), the surplus generation (spl), and the backup energy (bup). The triangles indicate how an increment Δ in wind+PV generation leads to an increase in d-iRE in the linear range of this curve and how d-iRE and spl share the increase in the saturation range. (b) Corresponding powers.

$L(t)$ during the year is maintained. The impact of alternative loads are briefly mentioned further below. 20 TWh are provided by hydro-electricity and the rest, 500 TWh, by wind and PV defining the annual iRE target $T_a = L_a - 20 \text{ TWh} = 500 \text{ TWh}$. In the model, the ratio of PV to wind energy is selected according to the “optimal mix” principle [14], offshore wind is arbitrarily set to 1/3 of the total wind generation. The energy and power shares of the optimal mix are typically: energy: $E_{PV} \sim 22\%$, $E_{W_{on}} \sim 52\%$, $E_{W_{off}} \sim 26\%$; power: $P_{PV} \sim 37\%$, $P_{W_{on}} \sim 51\%$, $P_{W_{off}} \sim 12\%$.

In the second step, the iRE electricity generation, E_{W+PV} , is varied. Variable is $f_{iRE} = E_{W+PV}/T_a$. In fig. 6. f_{iRE} is varied between $0 \leq f_{iRE} \leq 2$ implying an annually generated iRE electricity varying from 0 to 1000 TWh. $f_{iRE} = 1$ is denoted as “100% case” because wind and PV produce just the target T_a ($= 500 \text{ TWh}$).

Plotted in fig. 6(a) are the *annually* generated iRE electricity (t-iRE), the directly used one (d-iRE), surplus (spl), and backup (bup) energies and in fig. 6(b) the respective powers. The integral annual values of fig. 6(a) are deduced from time-dependent calculations. Directly used is the iRE power \leq the momentary target load $T(t)$; backup supplements iRE in cases where $t\text{-iRE}(t) < T(t)$: $bup(t) = T(t) - d\text{-iRE}(t)$; in case of excess-generation, surplus is the power which exceeds the momentary target load: $spl(t) = t\text{-iRE}(t) - T(t)$.

As shown in fig. 6(a), directly used electricity (d-iRE) increases initially linearly with f_{iRE} . At $f_{iRE} = 0$, backup starts at 500 TWh, the annual target T_a . Increasing d-iRE causes the backup energy, bup, to decrease in a symmetric form: $d\text{-iRE} + bup = T_a$. In this energy range, no surplus is generated because even the peaks of the iRE production

fall below the load and can directly be used. This changes at an iRE penetration of about 40%. From there on, iRE-surplus is generated. Beyond the 40% share, d-iRE and bup start to level off whereas the further growth of iRE power progressively generates surplus. The “100% case” is reached when iRE production $t_{\text{iRE}} = \text{target load } T_a$. In this case, surplus is equal to backup energy. From the 500 TWh generated, 390.3 TWh are directly used and 109.7 TWh appear as surplus necessitating the same amount as backup energy: In the 100% case, when iRES produces just as much as needed, under 2019 conditions 22% appear as surplus and have to be replaced by controllable residual power to meet the load. This is the reason why the promises of a 100% supply by renewable energies have to be scrutinized with some detail.

Beyond the 100% case, overproduction starts. The non-linear relation of d-iRE in the range of overproduction is an important feature of intermittent supply. The grey triangles in fig. 6(a) represent the response of d-iRE in case of an increment Δ in f_{iRE} . In the linear range, the increase in iRE energy (and power) leads to directly usable energy. In the saturation range, most of the increase is in the form of surplus and only a decreasing fraction can directly be used.

Surplus electricity used after transformation, storage and anew generation as secondary electricity will be in a different cost category as backup energy is in the period of iRE capacity build-up. In the saturation zone of d-iRE the question of supplementing or substituting renewable energies by alternative clean technologies like nuclear power arises. The cost assessment between renewable and nuclear technologies has actually to be done by comparing, *e.g.* nuclear electricity costs with those of secondary and less with the costs of primary iRES generation. The cheapest way is, of course, to adjust the load to generation (responsive load) and to reduce surplus production by demand adaptation. This important aspect represents the fourth major feature of the energy transition —the replacement of the traditional supply scheme of “generation follows the load” by “the load has to be adapted to generation”. It can, however, be doubted that such a scheme is viable at large scales facing the strong day-to-day generation variability preventing reliable day-ahead planning. The first field tests of demand adaptation yielded disappointing results in Germany [15].

Figure 6(b) plots the power values for the three parameters of relevance, the total iRE power (t_{iRE}), the backup and the surplus powers. iRE power and energy are linearly related. The model is set up linearly and possible nonlinearities introduced, *e.g.*, by transmission losses or peak power catenation are not considered. Two further features of intermittent power supply are of importance: 1) the power level of surplus power is high, much above the present peak load of ~ 80 GW. It will be necessary to catenate the power peaks in order to simplify and secure grid operation and limit the grid operational costs. Nevertheless, the remaining power level defines the consumer technologies like electrolyzers for hydrogen generation and thermal storage systems. 2) the backup power is only moderately reduced though the backup generation drops significantly in the range of overproduction (see fig. 6(a)). flh of the backup system falls to 540 h for $f_{\text{iRE}} = 2$ raising the question of operational economy. On the other hand, the backup system is needed to meet the demand and the economic concerns could be solved introducing a

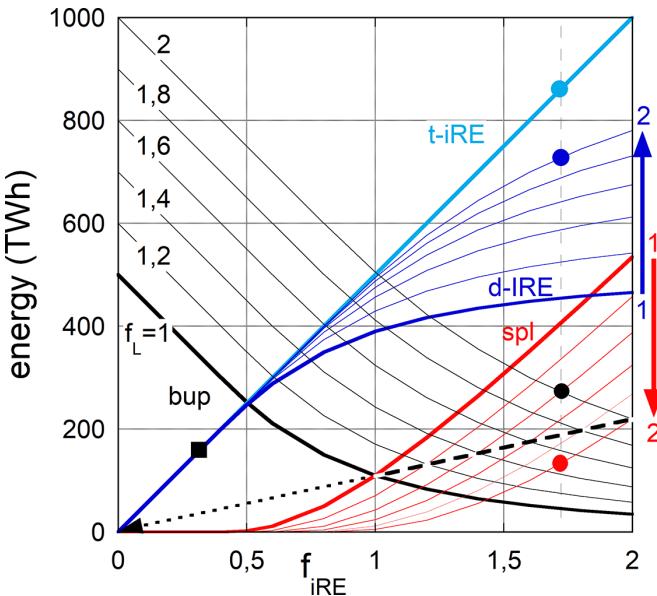


Fig. 7. – This diagram is an extension of fig. 6(a) when additionally, the consumption is varied. The consumption is parametrised by f_L = annual consumption/target load. The fat curves are reproduced from fig. 6 with $f_L = 1$. The thin lines represent the variation of b_{up} , $t\text{-iRE}$, $d\text{-iRE}$ and spl when f_L is varied from 1 to 2 (see arrows), whereas each set starts with the fat curves of $f_L = 1$. The dashed linear line denotes the special cases where $spl = b_{up}$. They are dubbed 100% cases because spl would conceptually allow replacing b_{up} by storage if storage losses were ignored. The square denotes the German situation in 2018; the dots the situation of Germany in 2045 expected from the AGORA installed iRES capacity [10] and processed on the basis of 2019 data.

so-called capacity market: In this case, backup operation is not funded for generating electricity rather for the potential to generate it.

The backup power $P_{b_{up}}$ drops by 18% at an overproduction factor of 2 (1000 TWh iRE generation). This reduction is often seen as evidence that wind, unlike PV power, contributes with a generation minimum P_{min} , which is always > 0 and which increases with total installed power. This is not truly the case [16]. For 2012 to 2020 (2016–2020), the average P_{min} of W_{on} (W_{off}) was 148 MW (0 MW); the annual increase of P_{min} of onshore wind was about 9 MW whereas the installations grew by 3.4 GW per year. The reduction of the $P_{b_{up}}$ peak is rather caused by PV power whose peak closely coincides with the load peak and moves the maximal backup demand toward the wings of the PV profile where consumption is reduced both in summer and winter.

5.2. Electricity consumption. – Up to now, we used the model to portray the conditions for an RES electricity generation of 520 TWh, 500 TWh from iRE and 20 TWh from hydro-electricity. Figure 7 shows the model results when we next allow the reference load to change between 500 TWh and 1000 TWh. In fig. 7 the demand is represented by

f_L = annual consumption/annual target being varied between $f_L = 1$ and 2. The results with $f_L = 1$ shown in fig. 6(a) are reproduced and given as thick lines in fig. 7. Directly used iRE energy (d-iRE) increases with f_L . This goes at the expense of surplus energy generation, which decreases with increasing f_L . Also, backup needs increase with f_L , representing the overall increase of demand. The black square denotes the end of 2021 situation of Germany with $f_{IRE} = 0.33$; 56 GW Won, 7.8 GW Woff and 56 GW PV having generated 165 TWh electricity. We have already mentioned (fig. 6(a)) that at $f_{IRE} = 1$ (100% case) surplus and backup energy curves cross. Disregarding losses, surplus could—in this case—directly replace backup. The dashed line denotes the crossing of these two parameters for $1 \leq f_L \leq 2$. Under optimal mix conditions with $E_{bup} = E_{spl}$, the two quantities increase linearly with f_{IRE} . The situation changes as soon as we introduce storage with transformation losses.

5.3. Storage. – Storage will eventually replace backup. Storage may fulfil two tasks: providing power and energy. Power for grid control will most probably be done by batteries; seasonal storage is in the TWh capacity range. In this case, the energy carrier has to be changed to one allowing cheap storage and this is not in the form of electricity rather of hydrogen as initial step. The transformation from electricity to hydrogen leads to energy losses. In addition, hydrogen is not simple to store. The lower calorific value of hydrogen is 3 kWh/Nm³ compared to 10 kWh/Nm³ of methane. Correspondingly larger has to be the storage volume. If required, hydrogen can be further transformed into ammoniac (*e.g.*, Haber-Bosch process) or carbon hydrates (*e.g.*, Fischer-Tropsch process employing additionally CO) but at the expense of further losses.

The basic scheme of producing secondary electricity is shown in fig. 8 [17]. Surplus represents primary electricity producing hydrogen via electrolysis, which is stored and used, *e.g.* in fuel cells to generate secondary electricity. The numbers in fig. 8 exemplify a case with surplus generation of 1.5 TWh, representing the average daily demand of electricity in Germany. Heat losses and separate electricity demand of the compressor are shown in the diagram. The water supply for the electrolyser of 243000 m³ compares with the daily consumption of the city of Munich. Because of the system losses, 1.5 TWh primary electricity yield 0.45 TWh secondary electricity. The system efficiency is 30%. We conclude that the price difference between primary and secondary electricity will at least be a factor of three.

In the following, the basic relations which govern storage will be discussed. In the modelling employed here, the storage is split up into a short-term (day) storage (DSt, with a capacity of 160 GWh) and a seasonal storage (SSt) with a capacity to be calculated. DSt is foreseen for grid services (not specified any further)⁽⁴⁾. Input for storage calculations are wind and PV power values and the load profile of a year, here of 2019. The storage is filled by surplus power which depends on f_{IRE} and f_L (see fig. 7). A storage fulfils the conditions that the “filling level” at the end of the year matches the one at the

⁽⁴⁾ Details of the storage calculations will be given in another publication.

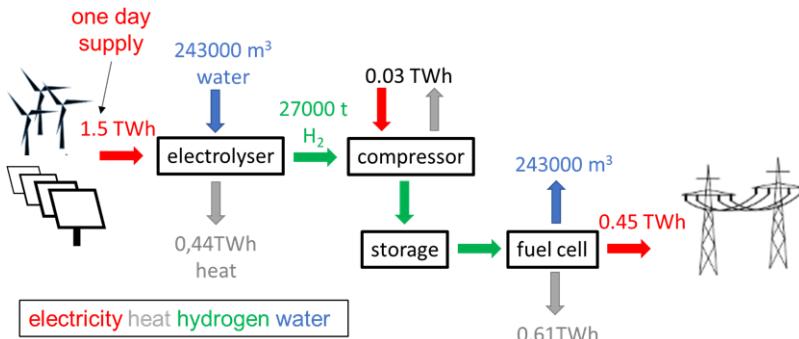


Fig. 8. – Schematic of a system to generate secondary electricity from primary iRE power using an electrolyser to produce hydrogen and a fuel cell to generate secondary electricity. The numbers exemplify the situation of one day of German electricity consumption of ~ 1.5 TWh. Heat generation and water consumption are also given. The schematic follows [17].

beginning (periodic boundary conditions). In the model, storage has to be fully emptied at least once a year. Then the peak storage level defines the capacity. Though the basic layout of the problem is linear, the storage filling shows a nonlinear behaviour. The work by the combined storage system should agree with the backup needs as presented in sect. 5'1 (see also fig. 6(a)). Transformation losses are proportional to the storage work. For calculating losses, we assume that DSt could be based on batteries with an efficiency of 85%; in case of seasonal storage, we assume transformation to hydrogen with an electrolyser *plant* efficiency of 70% followed by a fuel cell with 50% efficiency. In case the system produces surplus, after the load has been met, it is considered chemically stored energy in the form of hydrogen.

Figure 9 shows the combined storage capacity and storage work with the original backup energies to compare with as black dots and the hydrogen production from remaining surplus⁽⁵⁾. $f_L = 1.31$ in the case depicted in fig. 9, which corresponds to the political expectation in Germany for 2030⁽⁶⁾. Storage capacity and work increase with f_{IRE} and at $f_{IRE} = 1.625$ a maximum of 60 TWh capacity and 100 TWh of work is reached. Beyond this f_{IRE} value, both parameters decrease. In the rising branch, storage is limited by the availability of surplus; additional backup energy is still needed to meet the demand (difference to the dots in fig. 9). At the capacity/work maxima, processed surplus (= secondary electricity) just meets the demand and the storage work fully replaces backup. Beyond the capacity/work maxima, additional surplus is generated which can be turned into hydrogen as shown in fig. 9.

The storage analysis starts at $f_{IRE} = 1$, though surplus is generated starting with $f_{IRE} \sim 0.4$. For $f_{IRE} < 1$, large storage capacities are needed to contribute with storage

⁽⁵⁾ 4.5 kWh needed to generate 1 Nm³ H_2 .

⁽⁶⁾ At the end of 2020.

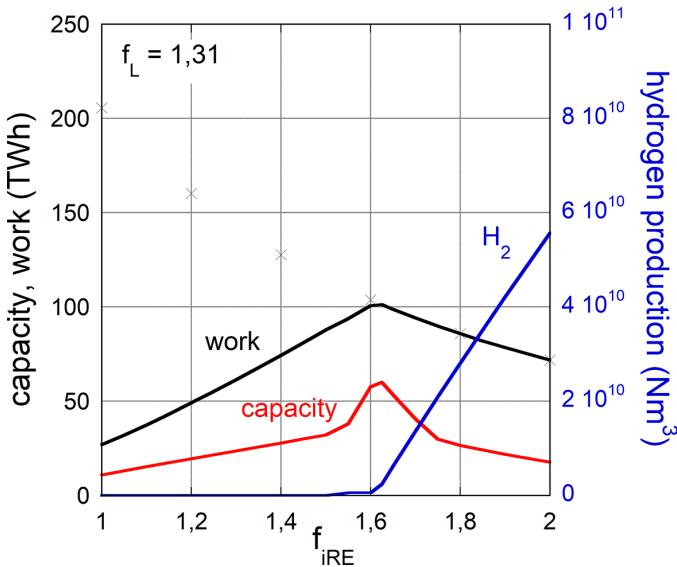


Fig. 9. – For $f_L = 1.31$, corresponding to the consumption of 650 TWh as expected for Germany for 2030 [18], storage capacity, storage work and possible hydrogen generation are plotted *versus* the normalised intermittent iRE share f_{iRE} . The symbols (×) represent backup energy in case of no storage.

work, which, on the other hand, is by far not able to replace the backup needs. This is the reason why storage enters the electricity transition at an advanced transition stage *e.g.* at $f_{iRE} \sim 1$. With increasing overproduction, the seasonal storage capacity decreases. At $f_L = f_{iRE} = 1$ storage capacity is 18 TWh based on 2019 conditions. The capacity drops down to 0.3 TWh in case of $f_L = 2$ and rises to 36 TWh, when f_{iRE} is allowed to increase to 2. The final electricity generation will be in the range $f_{iRE} > 1$ as the national potential has to be fully exploited to serve all energy consuming sectors. It is questionable whether under these conditions storage exclusively dedicated to secondary electricity generation is viable. Such storage systems must be able to operate under high power levels but, on the other hand, are limited to the production of low quantities of secondary electricity.

6. – The German situation: an example in numbers

Up to now, we have discussed the main characteristics of electricity generation mostly by wind and PV power using simulations based on the projection of historical data. For this purpose, we have employed model cases like the 100% case. Now, we will try to analyse the German energy and electricity demand and supply situation expected for 2045 in more detail and specifically try to provide actual numbers for major parameters. 2045 is the year in which, according to German politics, the country should be net-CO₂-emission free. Reference points for the assessment of the 2045 German energy and

electricity situation is an end electricity demand of about 520 TWh (an average value over the last decade) and an end energy need of about 2600 TWh.

As it is pointless to form one's own opinion on the actual iRE potential of Germany, we resort here to the figures provided by AGORA: $W_{on} = 145$ GW, $W_{off} = 70$ GW and PV = 385 GW [10]. The *average* energy generation from 2012 to 2020 calculated from the actual iRE electricity generation and scaled from the historical installations to those suggested by AGORA is 850 TWh per year. The highest value, 908 TWh, is from 2020, the lowest one, 723 TWh, from 2013. A year-to-year variation of 22% in iRE energy generation has to be considered. The year 2019, which we will use for a more in-depth analysis in the following, yielded 860 TWh. The comparison of 2021, a low-wind year, with 2020 exemplifies the high level of variability and demonstrates painfully the dependence of the electricity generation by iRE on unpredictable weather conditions. This aspect also sets a natural limit to the relevance of overly precise predictions.

For calculating the future electricity generation on the data basis of a specific year the full load hour figures, flh , of this specific year is used having in mind that further technical progress will partly be compensated by progressively less favourable generation sites. Nevertheless, the projected energy values can be expected to be lower limits. Figure 5 showed, however, that in the period 2012 to 2021, flh for the three iRE technologies strongly changed from year to year but shows only a weak upward trend in this period.

The annual iRE electricity generation has to be compared with the electricity demand of a completely de-carbonised economy. The future demand is, however, also difficult to predict. Maybe the basic electricity use might decrease thanks to the demographic factor, behaviour changes and the availability of low-consumption technologies; but industry 4.0, digitisation and smart systems will increase the demand. We stay with the present average value of 520 TWh for the net electricity consumption proper (ignoring losses) but new electricity consumers are mobility (~ 100 TWh), the use of heat pumps (~ 80 TWh), and the transformation of steel industry (40–80 TWh). The chemical industry association alone claims 628 TWh for a complete decarbonisation of its activities [19]. These figures would add up to more than 1400 TWh —much more than what can nationally be produced by RES.

AGORA concludes that Germany will need 1017 TWh electricity in 2045. Also, this lower amount cannot be provided by RES. In addition to the average iRE production of ~ 850 TWh, 20 TWh are generated by hydropower and possibly about 50 TWh can be added using biogas. This contribution can be questioned, however, because biomass may have to serve other energy sectors as mentioned above.

We consider two cases, the one with maximal hydrogen production from surplus electricity and the second one of electricity autonomy. How much hydrogen can Germany produce with its own means? The AGORA installations allow the generation of 860 TWh electricity under 2019 starting conditions. 705 TWh can be used directly⁽⁷⁾; 155 TWh are

⁽⁷⁾ This value is obtained using the present load profile. In case of an alternative —a load profile

surplus, which can be turned into 34 bn Nm³ of H₂, about twice the present hydrogen use of Germany's industry. In this case, 292 TWh electricity have to be imported or provided by a separate backup system in order to meet the AGORA electricity target. These results are marked as dots in fig. 7.

In the next step, we analyse the electricity autonomous situation of Germany in 2045. In this case, 550 TWh can be directly used. This is less than in the "hydrogen production case" because the additional losses in the fuel cell have to be accounted for. The rest is handled via a storage with a total capacity of 79 TWh. DSt contributes with 30 TWh and SSt with 92 TWh secondary electricity, in the sum 672 TWh. In this scheme, Germany can generate slightly more than the present *total* electricity generation (about 650 TWh). Considering 20 TWh of hydro-electricity, 325 TWh electricity have to be imported to meet the AGORA demand target. The transformation losses add up to 173 TWh, surpassing the storage work.

DSt contributes with 30 TWh at a storage capacity of 0.16 TWh, corresponding to 190 annual full-equivalent cycles, SSt with 92 TWh at a capacity of nominally 79 TWh. The storage capacity of 79 TWh depends on the peak power to be processed by SSt and can be reduced by catenating power peaks. Unlike to DSt, a dedicated seasonal storage for electricity seems to be unrealistic specifically when power specification, actual work, the number of full equivalent cycles, and transformation losses (168 TWh of SSt) are considered. More electricity can be directly used and less has to be imported if one abstains from the autonomous solution. In addition to short-term storage mostly for grid services (with 0.16 TWh, only about 2.5 hours of present electricity needs can be bridged) the results suggest to better generate hydrogen from surplus. Depending on the actual economic situation, secondary electricity can be imported or generated from the stock of nationally generated and imported hydrogen.

Regarding the net energy situation of Germany in 2045, in addition to 850 TWh iRE and 20 TWh hydro-electricity, Germany can generate nationally about 300 TWh biomass and about 240 TWh environmental heat in conjunction with heat pumps [20] and \sim 80 TWh solar thermal heat [21]. The energetically used share of biomass can hardly be increased. The present conditions lead already to a loss of bio-diversity and a strong reduction of insect and of bird populations. In total, the national energy production is in the range of 1500 TWh, about 1100 TWh short of the present average net energy consumption. Up to now, Germany's end energy consumption has slightly increased from 1990 to 2019. Savings of 1100 TWh do not seem to be possible on an evolutionary path.

All these numbers are indicative only and can be questioned in detail. Nevertheless, it is clear that Germany will remain an energy importer but, unlike in the past, not for low-level still abundant fossil fuels rather for electricity and hydrogen generated by renewable technologies.

constructed from the expected price variation— 773 TWh can be directly used and 224 TWh have to be imported (details to be published elsewhere).

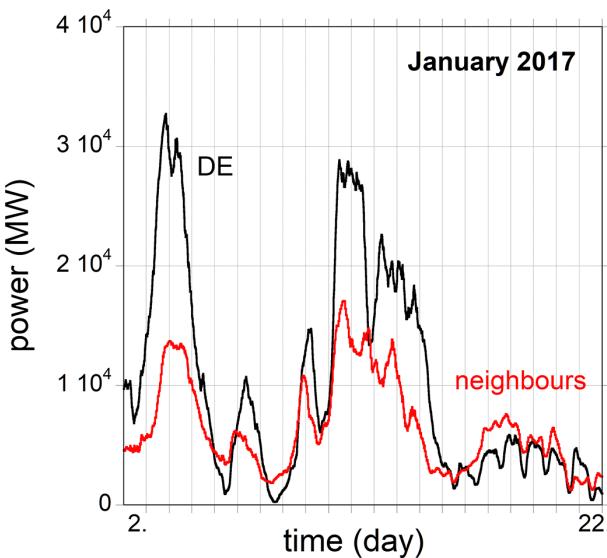


Fig. 10. – Onshore wind power generation of Germany and, in the sum, of its 9 neighbours for January 2017.

7. – Electricity import from Germany’s neighbours

With the AGORA electricity target of 1017 TWh, Germany has to annually import electricity of about 300 TWh. Because of transportation losses, the import should be from the closest neighbours. This implies a strong increase in EU export from the present level of typically 50 TWh of France and also exported by Germany in the recent years. In the future, it has to be renewable and possibly nuclear electricity to be exported. The export potential of RE electricity will depend on the weather pattern over Europe, which has typically an extension covering central and northern Europe. The consequence is that its neighbours also have wind and sun, when Germany enjoys these conditions and vice versa. Figure 10 compares wind power of Germany for three weeks in January 2017 with the one of its 9 neighbours. The comparison shows strong correlation [13]. The “lull-year” 2021 gave rise to a 13% lower onshore wind harvest in Germany and in the average to an 8% lower one in Germany’s neighbour states.

The analysis of wind power in Europe reveals two uncorrelated zones, a northern one and a southern one. The correlation matrix of fig. 11(left) shows high correlation between wind in Greece, Portugal, Spain, Romania and Italy and separately between the central and northern countries. Apart from autocorrelation, the Spaerman correlation coefficients vary between 0.8 and 0.25 from reddish to yellow. This splitting became also evident in the comparison of the onshore wind generation of 2020 and 2021. The northern countries experienced a reduction in W_{on} generation by -7% in the average whereas the obviously decoupled southern countries enjoyed a gain by +8%.

The consequence of the European weather pattern is that countries at larger distances

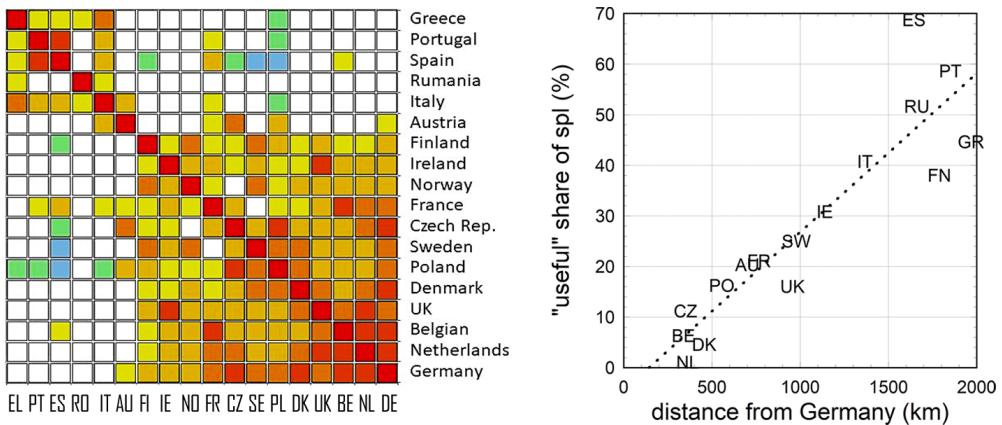


Fig. 11. – Left: Spaerman correlation matrix of onshore wind energy between the countries listed (2016). Wind generation is correlated in two well separated areas. Apart from autocorrelation, the correlation coefficients vary from reddish (0.8) to yellow (0.25). Only a small correlation exists between the southern and northern countries. Right: the “useful” share of a country’s surplus is plotted against the distance of the wind park core of this country from Germany’s wind park core (see text). “Useful” is defined as surplus energy of a country at a moment when Germany actually needs backup.

from Germany produce a higher share of “useful” surplus, defined as being available when Germany is in need (of backup power). Figure 11(right) shows the results of this analysis for December 2016 data. Plotted is the national share of normalised surplus summed up during periods of backup needs of Germany against the distance from Germany. A national wind park centre was defined from the averaged latitude and longitude readings of wind parks [22] whereas the individual wind park contribution was weighted by the installed power. The separation of these centres to the one of Germany yielded the abscissa in fig. 11(right).

The import of electricity requires long high-voltage transmission lines and powerful interconnectors at the borders (presently 18.5 GW for Germany). Transmission lines are unpopular as Germany itself has experienced in its efforts to build electricity “highways” from Thuringia to the neighbour state Bavaria. Dismissive public positions can be expected specifically when transfer lines do not serve the national supply needs.

As the German electricity import needs go beyond any precedent, electricity import at the necessary level will hardly be possible when all neighbours of Germany also use mostly RES. The consequence is that Germany has predominantly to import, *e.g.*, hydrogen to generate secondary electricity to fill the gap. 300 TWh secondary electricity correspond to about 900 TWh primary RES electricity generated by exporting countries. This is comparable to the national potential of Germany as we have seen above. To meet the future electricity needs of Germany, a similar build-up of iRE installations is necessary together with the necessary hydrogen/ammoniac transformation technology by future trading partners. It is not clear which countries qualify for hydrogen export at these

levels and be ready along the foreseen time scales. The qualification is based on sufficient sun, wind and ultra-clean water availability for electrolysis and large port capabilities for hydrogen export. 100 TWh energy correspond to 3 mill tons of hydrogen based on the lower calorific value. Transported as liquid, about 93 ships of the present specification [23] have to arrive in Germany every day. The transport in the form of ammoniac implies gravimetrically predominantly the transport of nitrogen.

8. – Nuclear energy

During writing of this paper, the European Commission has published its draft paper on the EU Taxonomy Regulations [27] stating that nuclear energy can contribute to decarbonisation. The comparison of CO₂ emissions for power generation of France and Germany supports the position of the Commission. Figure 12(a) shows the historical development of the electricity mix of the two neighbour countries starting from 1970 [28]. France developed nuclear power, Germany burnt predominantly coal and is for years the world's largest user of lignite, the “dirtiest” form of coal. This is reflected by the CO₂ emission as compared in fig. 12(b). For electricity generation France emitted about 300 mill tons per year of CO₂ less than Germany over 4 decades. This is a substantial service to the environment. The red squares in fig. 12(b) show the decrease of CO₂ emission in case Germany had kept its nuclear power arsenal and moved out of lignite in the steps nuclear energy was removed from the grid. Such an act would have helped the environment.

As Germany stopped three nuclear power stations at the end of 2021, 103 nuclear power reactors operate in 13 EU countries producing 1/4 of the electricity. Thus 70% of the EU population is served by nuclear power. The future of nuclear energy is not spelled out in detail. Some countries plan to terminate nuclear power (Belgium, Germany, Spain), others to prolong it to 60 years (Hungary, Sweden, Switzerland). Finally, there is a group of countries which builds new reactors or has plans to do so (Belarus, Czech Rep., Finland, France, Netherlands, Hungary, Poland, UK but also Belgium⁽⁸⁾). It can be expected that these plans will not be realised in all cases but it can be expected that nuclear power will be in operation in Europe up to 2050 and beyond. A critical issue specifically for France is, however, the aging of the pioneering reactors of the 70ies.

The discussion on the EU Taxonomy proposal is around the term “sustainability”. This is a very complex criteria also for RES facing the material and mineral demands as presented in sect. 3 and the little hope that critical materials can efficiently be recycled in near future. A rather obvious criteria would be whether there is a need for clean energy sources in addition to RES. The analysis of the Germany strategy shows that such a need indeed exists. If France uses its potential for RES, which seems to be higher than the one of Germany, it still can add short of 400 TWh of nuclear electricity, which is

⁽⁸⁾ There are recent plans to consider small modular reactors (SMR) for Belgium.

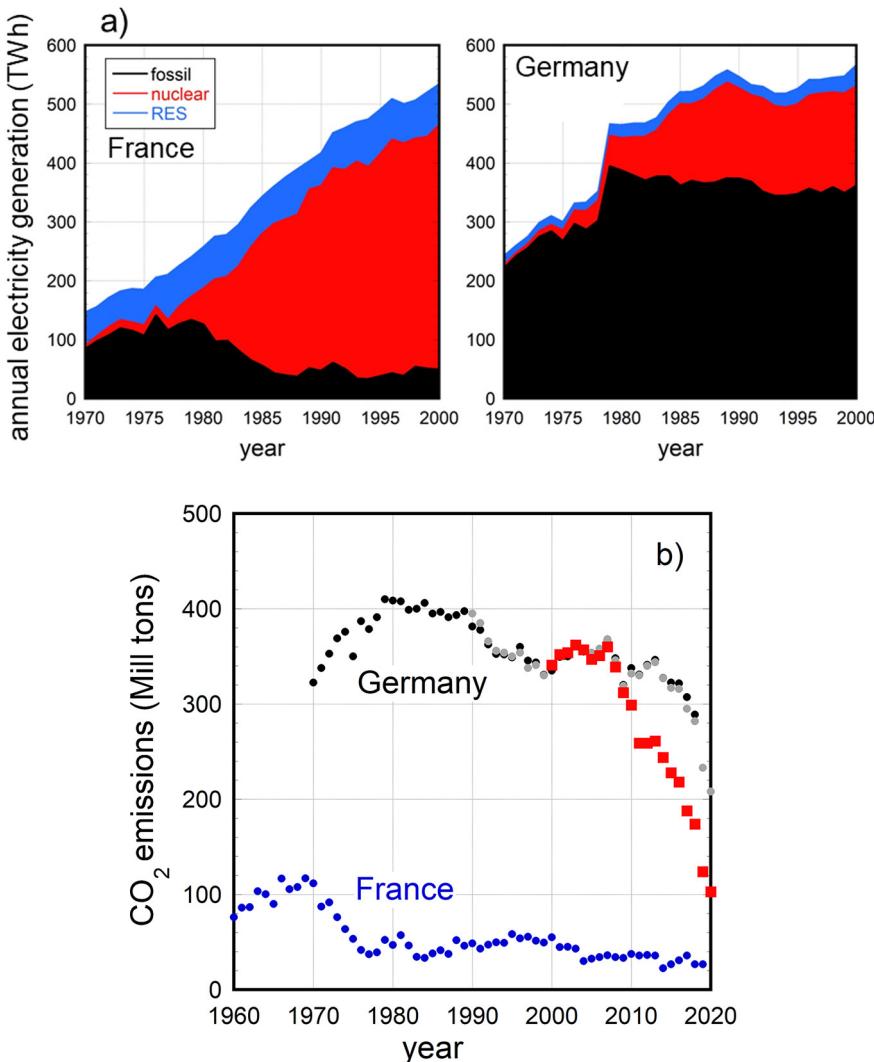


Fig. 12. – (a) Annual electricity generation of France and Germany from 1970 to 2000 split up into fossil, nuclear and RES shares. (b) CO₂ emission from electricity generation of France and Germany starting from 1960 or 1970, respectively. Data sources: black and blue: EDGAR-EU [24]; the grey dots represent emission data averaged from UBA [25] and STATISTA [26] compilations. The red squares represent Germany's CO₂ emissions in case nuclear energy had remained at the year 2000-level and lignite had been reduced in the following years in the steps nuclear energy was removed from the grid.

a tremendous asset facing energy shortages or the environmental damages of low-power density technologies operated in densely populated countries.

The nuclear accident of Chernobyl was caused by bad technology (positive void coefficient) and an irresponsible experiment carried out with the Soviet RBMK reactor

type. The Fukushima accident [29] was so dramatic because the protection wall against Tsunamis was not high enough ignoring historical experience. The safety installations (rupture discs, use of hydrogen recombiners) did not meet modern standards; backup power supplies were not correctly placed. These deficiencies were obviously only possible because regulation bodies did not function properly. The official National Diet report on the Fukushima accident states [30]: *The incestuous relationships that existed between regulators and business entities must not be allowed to develop again.* All these problems can be avoided by proven technology and independent and transparent regulations.

Nuclear waste storage is for sure a severe problem with which the above-mentioned European nuclear countries have to deal with. There is no way out and a best effort solution has to be found by each nuclear country. Finland will be first to open its waste repository in ~ 2025 in Onkalo. This repository will finally be sealed. It might be advisable to leave repositories open and await the results from MYHRRA transmutation reactor [31] and Gen-IV reactor concepts [32] which are expected to shorten the decay time of nuclear waste. In this case, the public position to waste handling and disposal could change over the next years.

The operation of nuclear power stations in load-following mode has been demonstrated by many power reactors with the conclusion of a “*full complementarity between nuclear and renewable energies*” [33]. It seems to be specifically possible to cope with the daily rise and fall of PV power which would lead to two output variations a day, which seem to be manageable.

A frequent objection against the use of nuclear energy is the high capital costs and the resulting high electricity costs. As argued in sect. 5.1, in case of iRE, the electricity costs of nuclear power has to be compared not with those of primary electricity generation rather with those of the inescapable production of secondary electricity.

9. – Final remarks

We come back to the beginning of this paper. Because of the few options for a clean electricity and energy supply, the strategies seem to be clear —to maximally use the available natural options like hydro-electricity, biomass and geothermal power. In many cases, the dominant supply must come from wind and solar power. The employment of CCS may be required to handle unavoidable industrial CO₂ emissions, *e.g.*, in the production of cement [34]. The use of nuclear power is a political and societal issue. Germany observes strictly a schedule of terminating secured power replacing the missing power by a strongly delayed rollout plan for iRE and the necessary grid expansion. With such an approach, Germany violates a proven electricity supply principle of Europe that each country secures first its own demand. With predominantly iRE, electricity supply safe-guarding is not possible. Being the European country with the largest electricity consumption, the German electricity strategy has strong consequences on her neighbours and should be of concern. The European-wide grid separation from Jan. 8th, 2021 is a good example of what could happen more frequently and more severely in the future [35].

We have seen that a focus on iRE demands the use of a backup system, which uses preferentially gas as long as hydrogen is not available in larger quantities. Burning gas has lower CO₂ emissions as consequence but CH₄ leakage on the way from the gas fields in Siberia to the user in Europe is specifically detrimental as methane has a much larger global warming potential than CO₂ has (about a factor 30, averaged over 100 years). For $f_{iRE} = 1$, the backup capacity is 70 GW, 10% less than peak power. 7.5 GW could be covered by hydro and biogas electricity. According to [36] 82 gas power stations with, in the sum, 22.5 GW electrical power are operated in Germany in 2020. To meet the backup needs, additional 40–50 GW have to be realised, which correspond to 150 gas power stations of the 300 MW_{el} class (corresponding to the average power of the presently installed units). Up to 2045, every two months a new unit has to be connected to the grid. 2/3 of the present gas power stations are of GuD type producing electricity and heat. It can be questioned whether their specific dedication allows them to provide electricity services only. The consequences of the Russian-Ukrainian war on international gas trade could jeopardize the strategy to supplement the expansion of iRES by a backup system based on burning gas.

The major installation thrust has to be the expansion of wind and PV power. To reach the AGORA 2045 development goals for the three iRE technologies, the annual additions of onshore, offshore and PV power have to be 3.8, 2.6 and 13.6 GW. The average expansion rates from 2010 to 2021⁽⁹⁾ were 2.8, 1.0, and 4.1 GW per year; the peak values were 5.3 (2017), 2.3 (2015), and 7.6 (2012) GW. For all cases, the expansion rate has to be doubled compared to the average historical values and kept at this level for more than two decades. Only in case of onshore wind, the future expansion rate has already been demonstrated. One has to consider, however, that, in addition, end-of-life systems have to be replaced. Assuming a lifetime of 25 years, the maximal addition rates for W_{on}, W_{off} and PV rise to 9.1, 4.9 and 21 GW per year. It is questionable whether such goals can be met. In 2021, about 30 GW of onshore wind have been installed worldwide outside of China.

For Germany, this ambitious expansion of wind and PV power necessitates additionally thousands of km of high-voltage lines and 100 thousands of middle- and low-voltage lines either newly built or upgraded. This development has already started years ago whereas the intermediate targets have rarely been reached.

A large part of primary energy is used to heat the housing stock. In Germany 2020, 50% of it is heated by gas, 25% by oil and only 2.6% by heat pumps [37]. It is another tremendous task to replace oil and gas heating specifically in older buildings with their additional difficulties to realise proper thermal insulation.

The purpose of these examples is to highlight the tremendous task of the energy transformation for a still strongly industrialised country, which should happen within a short time frame in spite of rather unfavourable boundary conditions —the demographic factor, rising material and energy costs, lack of specialists and craftsmen.

⁽⁹⁾ In case of offshore wind from 2016 to 2021.

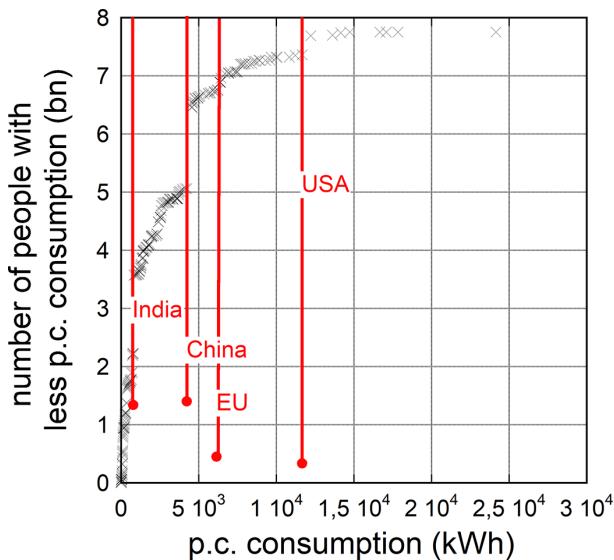


Fig. 13. – Plotted is the number of people with less *per capita* (p.c.) electricity consumption than the respective number of it at the abscissa. The individual data of India, China, and the USA are given as red dots. The vertical lines mark the gaps in the ordinate when the population of the respective country is added. For the European Union, there is no gap because in this case the individual countries are plotted.

But the electricity supply and consumption conditions of Germany and the EU are not representative with 6440 kWh/p.c. or 6156 kWh/p.c., respectively. Figure 13 addresses the accessibility to electricity and shows the number of people without access to a specified per capita (p.c.) electricity consumption (abscissa). Taking the example of

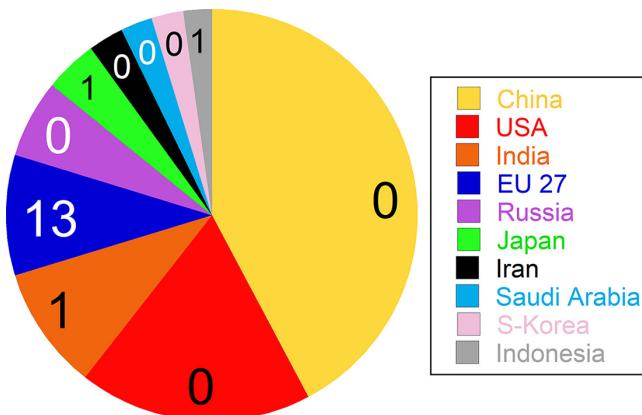


Fig. 14. – Pie chart of the 2020 CO₂ emission of the primary 10 emitters [39] and the number of United Nations COP conferences organised by the respective countries [40].

the EU (red dot), close to 7 bn people have to comply with less p.c. electricity use. The p.c. electricity consumption for India, China, and USA is given as red dots. The vertical lines mark the gaps in the curve where their population enters the graph. A gap is not shown for the EU because the EU members are plotted individually.

This diagram plots the electricity consumption because electricity will be the future primary energy. Its technical development status is crucial for the energy transformation up to 2050. The graph demonstrates that today only a low level of electricity supply exists for, by far, the majority of the world population. This is the situation though today the energy supply is by established technologies and up to now cheap and available fossil fuels. It is difficult to imagine that the countries with supply limitations, *e.g.*, the African generations to come (see fig. 1) will be able to master their energy transition to the use of clean electricity, which is anyway less of a transition rather a system set-up.

Considering the political interests and agendas of the five main emitters —China, USA, Europe, India, and Russia— one may also worry in their case about a sustainable effort to go jointly through the transition up to 2050. Figure 14 gives the number of COP conferences organised by different countries on the background of their CO₂ emission share [38]. The COP conference is the conference of the parties, the UN climate conference. China and the US, the largest CO₂ emitters, have not yet organised a COP conference. India has organised one, Russia none. Europe has organised 13, the last one in Glasgow in 2021. The political interest on a concerted approach to fight climate change seems to strongly differ and the EU and Europe's governments have to be careful that the climate change issue will not become their exclusive project.

Because of the obvious risk of failure, it is mandatory to take additionally appropriate measures of protection against the consequences of global warming. Politics may not exclusively concentrate on prevention but has to include adaptation measures. Unlike the global efforts, adaptation measures promise immediate and traceable effects. This is a wide field which should receive more attention whereas science will also play a crucial role therein.

* * *

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