

EPS-SIF Energy Summer School 2019: Concluding remarks

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Summary. — This paper is based on the last talk of the summer school. The intention of the talk was not to repeat any highlights of the school, rather to place the energy issue in a wider frame of global issues like global warming and the global responses to this threat. Therefore, I tried to compile —where possible— new data which inform the audience on the present stage of the energy transition toward carbon-free technologies and some expected future trends. The largest hopes for a successful transformation are connected to renewable energy forms. This field is discussed here mostly from a system point of view whereas I resort heavily to examples from Germany. The most obvious reason is that I am familiar with the German development and have access to the most relevant data. On the other hand, the German experience is of importance for other highly industrialised economies and its development affects other countries because of its central location.

1769 is often seen as the beginning of the 1st industrial revolution when James Watt received the patent for his advanced version of the steam engine. In the following years the device was further developed and became a mobile engine to do mechanical work wherever needed. Because of its versatility it eventually revolutionised the then existing processes in mining, agriculture and fabrication, let to innovations and finally changed the ways of transportation. Technology, starting with the steam engine, made it possible that energy was provided as mankind needed it. The original fuel, wood, was replaced

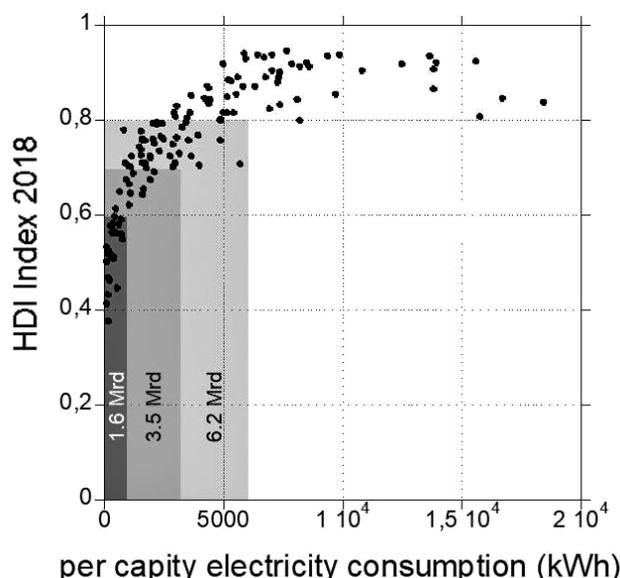


Fig. 1. – The Human Development Index, HDI, *vs.* the annual electricity consumption *per capita*. The shaded areas indicate the number of people with an HDI less than 0.6, 0.7, and 0.8, respectively. Data are taken from United Nations Human Development Reports, the 2014 electrical data are taken from the World Bank, the 2017 ones from the IEA atlas of energy. For comparison, the electrical data are linearly extrapolated to 2018. Data from Norway (0.954, 23 kWh) and Iceland (0.938, 54 kWh) are omitted.

by coal firing the steam engine. Eventually oil and gas fields could be exploited and more and more versatile and convenient forms of fossil fuels were available.

Industrialisation came at a time of strongly improved health care and agricultural production. Improved water and food quality and the reduction of infectious diseases increased the birth and reduced the death rates. Thanks to nitrogen trade and the use of artificial fertilisers more people could be nourished by a hectare of land. Industry provided the goods of a rising population and jobs outside agriculture. This development spread all over the world with the consequence that population growth continues up to today and will further continue during this century. People consume energy and this consumption grew in parallel to the population growth and will continue to grow.

In addition, also the *per capita* use of energy increases. Life quality, expressed *e.g.* by the Human Development Index, HDI, a qualifier based on life expectation, education and *per capita* gross national income depends on the availability of energy, specifically of electricity as shown in fig. 1. Countries with high specific electricity consumption have distinctively higher HDI values. This dependence is the driving force for individuals to increase their energy consumptions and for countries, to install the necessary generation technologies. As a consequence, the world energy consumption increases faster than the world population. Figure 2 shows this dependence starting with the time of James

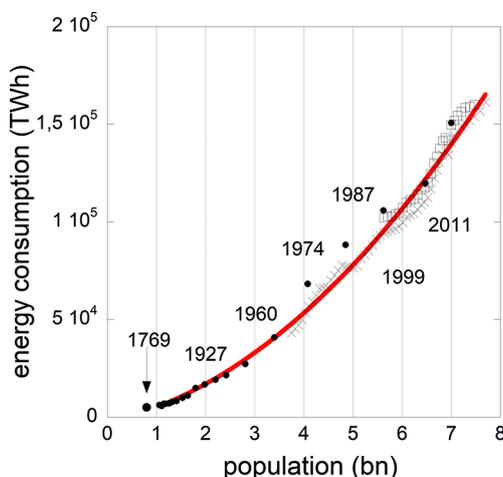


Fig. 2. – Global energy consumption growth *vs.* the population growth starting in 1769 when James Watt’s patent was accepted. Data are collected from various internet sources. The red line is a parabolic fit.

Watt. The red curve is a parabolic fit to the data showing a quadratic rise of energy consumption with population.

Coal, gas and oil, specifically for mobility, are the backbone of our industrial and non-industrial activities. Figure 3 compares the sources used for primary energy consumption of the world with those of Germany. The world data reflect the average situation of relevance for the vast majority of people, those of Germany of a highly developed, highly industrialised and traditionally technology oriented country. The fossil fuel share of worldwide consumption is 86%, the one of Germany 80% —not much lower. The nuclear power share of Germany is presently larger than that of the world but this will change when Germany finally abandons nuclear power in 2022. The German use of hydro power plus other renewable energies (REs) is slightly larger than that of the world average. Because of its geographical location, Germany is not a country well served by REs. The slight advantage in CO₂-free energy consumption of Germany compared to the world is the outcome of a tremendous effort over the last 20 years replacing its traditional but no longer acceptable supply technologies by wind, PV power and energy from biomass. In 2019, Germany produced ~ 40% of its electricity production by REs corresponding to ~ 10% of its end energy use. The lion’s share of this CO₂-free production serves the replacement of nuclear power —another CO₂-free system [1].

The similarity of the world primary energy mix with the one of Germany shows the tremendous dominance of fossil fuels and the nearly ignorable impact of industrial development and technology orientation on the existing energy mix. The comparison shown in fig. 3 also demonstrates the complexity of the task to change energy technology. One may have to be afraid-of that at present but also for the foreseeable future life conditions in developing countries can only be improved with fossil fuels. China is a

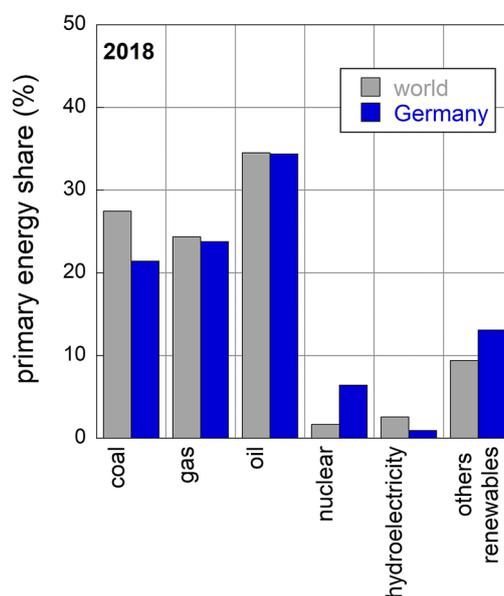


Fig. 3. – The primary energy use of the world and of Germany is split up into the various sources. The world data represent the average situation, the ones of Germany those of a historically technology oriented country. Data from “Our World in Data”.

country decisive for the world climate. China develops practically all energy technologies. In 2018, 41 GW of fossil, 11 GW nuclear, 21 GW wind and 45 GW solar power have been commissioned. According to the South China Morning Post additionally 121 GW coal power stations are under construction. China is also involved in the export of about 100 GW coal power stations. China is the precedence for a successful economic development on the basis of fossil fuels, specifically coal.

Because of the importance of fossil fuels and the difficulties to replace them, the IEA expects an ongoing growth of them up to the end of the projection period, 2040. The results of fig. 4 are taken from the IEA Outlook 2019 and correspond to the New Policies Scenario, NPS, which is based on present national planning aligned, to a certain extent, on environmental commitments. In 2040, it is expected that oil, coal, gas and clean energies (nuclear and REs) cover the demand with about 25% share for each of them.

Other circumstances which will stabilise the use of fossil fuels over the next years and possibly decades is the sheer economic power behind their exploitation and use. Seven out of the 10 top-selling corporations in the world depend on the use of oil. They range from number 2 (see footnote⁽¹⁾), Synopec, the Chinese petrochemical cooperation with a sales volume corresponding to the federal household of Germany, to Toyota, the Japanese car producer at place #8.

⁽¹⁾ Number 1 is the US retail company Walmart.

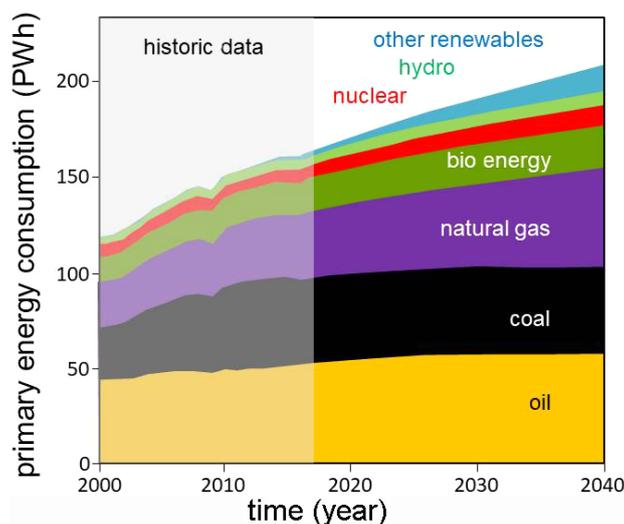


Fig. 4. – Primary energy consumption *vs.* time. The range of the historical data is indicated. The rest up to 2040 are the outcome of the IEA New Policies Scenario, NPS. The graph is reproduced from the IEA Outlook 2019.

In the past, the intense uses of fossil fuel led to concerns about their range of coverage—in technical terms by the ratio R/P of the reserves R to the annual production P . R denotes the reserves, which can be exploited under presently economic conditions. For coal the R/P values vary between 120–150 years, for oil and gas they are about 50 years. The concept behind the R/P value is a generation curve which has a maximum of maximal exploitation, the Hubbert peak. Thereafter, the exploitation declines to zero, defining the present-day R/P ratio. The Hubbert curve is correct for individual fossil fuel fields but not necessarily for the world production and consumption when new fields are discovered or new extraction technologies are developed as is the case, *e.g.*, with fracking. If the new reserves are powerful, the Hubbert curve may develop another peak. Therefore, the R/P values have to be taken with caution—but meanwhile, they are irrelevant anyway because of global warming as corollary of the fossil fuel use and the CO₂ emission into the atmosphere. About 37 bn tons of CO₂ or 43 bn tons of CO₂eq green-house gases have been emitted into the atmosphere in 2019. The 1.5 °C limit of the Paris agreement would allow about 400, the 2 °C limit about 1000 bn additional tons of CO₂eq. With present emissions, these limits are reached in 11 or 27 years, respectively, distinctively earlier than the R/P values would predict the end of the reserves. Therefore, also the discrimination between reserves and the much longer lasting resources is irrelevant for the still tolerable supply with fossil fuels. The environmental limits do allow only 1/3 of the fossil fuel stock be used and transformed into CO₂ least carbon capture and sequestration (CCS) technology is considered.

It is undisputed that both the CO₂ concentration in the atmosphere and global temperature rise. The CO₂ emission increases driven by the anthropogenic fossil fuel use.

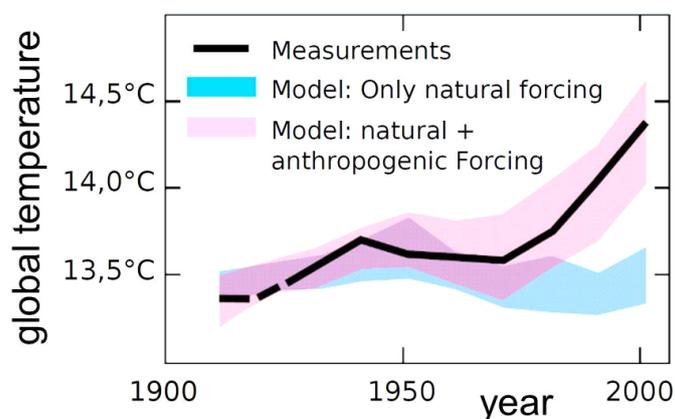


Fig. 5. – The evolution of the global temperature is plotted from 1900 to 2000 and compared with two model calculations —the blue one considering only natural forcing effects, the red one including the man-made contribution. The graph is a copy from the presentation by D. Notz.

The ratio of C13/C14 in the atmosphere decreases in the period of global CO₂ increase toward the natural level of this ratio as observed in plants buried hundreds of millions of years ago. The conclusion is that the origin of the additional CO₂ lays in the fossil fuel reservoirs. In addition to the temperature rise, the sea-level rises, glaciers and the ice in the arctic areas melt and the acidification of sea-water continues. The atmospheric JET stream started to meander leading to longer stable weather conditions as experienced specifically in Europe during the summers of the last years.

The causality between CO₂-increase and global temperature rise can only be resolved by climate modelling. Figure 5 shows an important and easily digestible outcome from the IPCC efforts, the reproduction of the global temperature rise over most of the last century. Compared are the temperature evolutions for the case of natural forcing, yielding rather constant temperature conditions and when the anthropogenic CO₂-forcing is added. With this addition, the observed temperature increase⁽²⁾ from 1980 on is well reproduced.

Anthropogenic climate change with an increase of the global temperature has many sceptics. But the complexity of climate predictions is large and back-of-the-envelope computations —often allowing to narrow down and sort out major effects and their possible impact— are simply not applicable. The models are complex and their use needs large computer facilities. There is no concise theory which could compete with

⁽²⁾ The analysis of so-called hiatus of the last years is not included in this figure. In [2] it is shown that the discrepancy between the actual temperature development and the modelling is not caused by the assumption of an unrealistic climate sensitivity on radiative forcing rather depends on aspects of climate variability like the heat transfer between the atmosphere and the oceans.

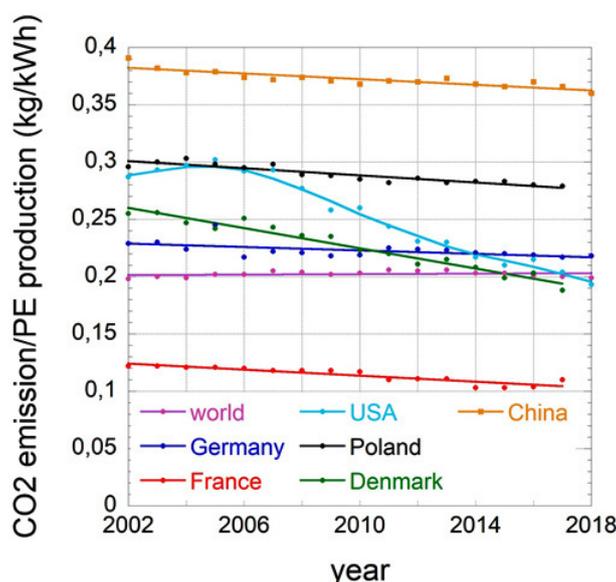


Fig. 6. – The ratio CO2 emission to primary energy (PE) production is used as a simple qualifier for the employed technology in all energy consuming sectors and plotted *vs.* time for various countries with quite different economic, technical, and societal background. The emission data are from OECD, the primary energy data from the German ministry of economy and energy.

fig. 5 and quantitatively explain the temperature rise along an alternative mechanism. As a consequence, those interested but not directly working in the field have to identify reliable information sources to be well informed. In joint meetings with representatives of the IPCC line I mostly found the arguments of the “climate sceptics” rather weak and non-convincing. Anyway, the progressing acidification of sea-water and the CO₂-induced prohibition of the water, oxygen and CO₂ exchange through the stomata of plants will more and more direct the attention on negative impacts of enhanced emissions on the CO₂ concentration itself.

To what extent and with what success does the world respond to this tremendous challenge? The ratio of CO₂ emission E to primary energy use PE can be considered as a rough qualifier for the cleanliness of the nationally employed energy supply technology. The primary energy use represents all energy consuming sectors. Figure 6 plots this ratio for several relevant countries over the last 16 years.

China has a high E/PE ratio mostly because of the dominance of coal in the electricity generation. The ratio for Poland, also producing most of its electricity by coal, is lower and decreases with the same slope as in case of China. USA has left the coal dominated level and has reduced its CO₂ emission thanks to the availability and use of shale gas. Germany has a very slow reduction of the E/PE ratio because most of the CO₂-free production of REs goes primarily into the replacement of nuclear power. In the considered period, Germany has replaced only 44 TWh of coal generated electricity. 85 TWh were used to replace nuclear power. The true benefits of nuclear power use are reflected by

the French data. The ratio is much lower than in all the other countries considered and decreases with the same slope as in case of China and Poland. The progress reflected by E/PE is distinctively larger in case of Denmark. Denmark used and still uses coal for electricity production but has an aggressive programme to change to wind power. It also benefits from its partnership in the Nordic grid with access to the clean electricity production of Norway and Sweden and the storage capacities of Norway. Denmark is an importer, Norway and Sweden are exporters of electricity.

There are not too many technical solutions available for CO₂-free energy supply. Only with CCS technologies, the use of fossil fuels may be justified in the future. Other CO₂-free options are the nuclear technologies, fission and fusion, and the renewable energies in their various forms as presented to and discussed in this summer school. Energy saving is another general requirement, which will be the driving force behind many future technological developments in conjunction with smart grids, -homes and -cities. However, most of these new technologies will consume electricity. It is therefore an unfavourable constellation that in the critical period of the energy transition electricity prices are high in many countries because of large state taxes and other dues preventing thus incentives for the market penetration of new energy saving techniques.

From the expectations of IEA as shown in fig. 4, the consideration and development of CCS technologies seem to be essential both for electricity production and possibly even more so for industrial processes [3]. Several techniques allow the separation of CO₂ from the flue-gas at the power station. The underground storage requires, however, detailed knowledge of the local geological conditions. Norway has experience applying CCS since several decades. CO₂, which accrues together with gas and oil extraction is not allowed to be released to the environment in Norway rather has to be pressed back into the voids. Of course, this technique also allows to better exploiting repositories. The notion of an underground storage in one's neighbourhood is, however, not popular. Therefore, CCS is not allowed in many countries. Research into this field and pilot projects have often been stopped. This is a mistake and hardly justifiable. In many of the countries where CCS is not allowed the consumption based CO₂ emission clearly surpasses the one of national production. The difference is due to the import of commodities produced elsewhere by emitting CO₂ (traded embodied emissions). The difference is typically more than 10% (for energy related CO₂ emissions). One could expect that CCS technology is developed, not necessarily for the purpose of self-use rather to be offered to other countries with difficulties to simply replace coal. Another motivation for the storage of CO₂ is the availability of this base product for future CCU —carbon capture and use— technologies, *e.g.*, in the frame of producing higher hydrocarbons promising higher energy densities compared to “green hydrogen”.

In 30 countries, about 450 nuclear power stations produce electricity contributing in total with about 10% to global electricity generation⁽³⁾. About 50 reactors are under

⁽³⁾ <https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx>.

construction. Bangladesh (two Russian VVER-1200; construction has started in 2017), Belarus (two VVER-1200; start of operation expected 2020), Turkey (four VVER-1200; construction start of the first one in 2018), and United Arab Emirates (5.6 GWe by a South Korean consortium; construction started 2012) will employ nuclear power for the first time.

In many consumer countries, nuclear energy is highly unpopular. For a longer perspective of this technology, new reactor concepts are necessary, whose basic principles are well known but still require intensive R&D. Those are, however, not pursued, on the contrary, science and technology oriented countries move out of nuclear energy. The most prominent case is Germany. German politics has compared the threats of global warming with those of nuclear power operation and, in the aftermath of the TV pictures from Fukushima, concluded that it can be justified to use nuclear power for further 11 years but not longer.

The major arguments against fission power are operational safety, proliferation and radioactive waste disposal. The environmental benefits of nuclear energy are obvious as the comparison between France and Germany shows—in location and economy two rather similar nations. 2017, France generated its electricity (579 TWh) largely CO₂-free by 72% nuclear, 10% hydropower and 8% renewable energies from wind, PV and biomass (the rest is from other sources). Germany produced 646 TWh electricity with 50% fossil, 33% REs and 12% nuclear. The specific CO₂ emissions associated with the electricity production are 76 g/kWh for France and 486 g/kWh for Germany⁽⁴⁾. The consequence is that Germany emits 240 million tonnes CO₂ per year more than France. The tremendous built-up of REs in Germany in parallel to the decommissioning of nuclear power has saved just 167 million tons of greenhouse gases in 2018 compared to the emission in 2002. France has been contributing to climate protection for more than 30 years. For decades, France has been producing electricity at climate-friendly levels whereas Germany threatens to miss its 2020 climate goal and will need a few more decades to meet the French emission quality.

Fusion is still a research field. A crucial role for the advancement of fusion is played by ITER, the International Thermonuclear Experimental Reactor, under construction in Cadarache in France. The start of ITER is planned for 2025. The critical results are presently expected middle of the 30ies. In case of success, fusion electricity can contribute to the last decades of this century but hardly earlier.

The largest hopes for CO₂-free electricity and energy production rest with renewable energy forms: solar- and wind power, bioenergy, hydroelectricity and the more restricted forms: geothermal and wave power, requiring specific geological or geographical circumstances. The further expansion of hydroelectricity is limited because of its geographical requirements but also its ecological impact.

According to IEA biofuels and biogenic waste contributed with 9.5% to the global total primary energy supply (TPES) in 2017. However, the use of biomass is limited

⁽⁴⁾ Including upstream-processes; without them the French value is 37 g/kWh.

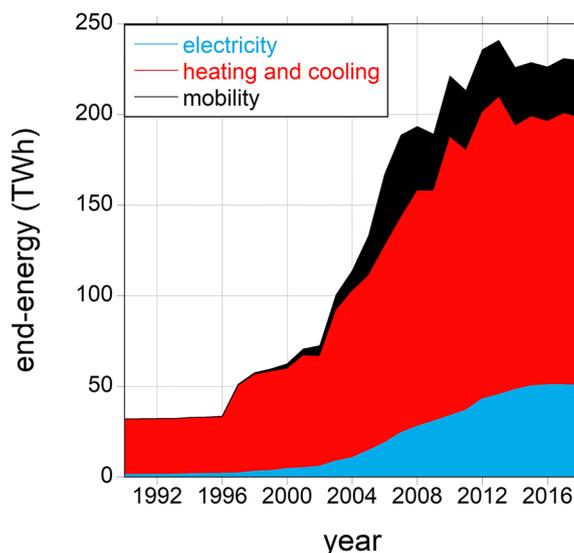


Fig. 7. – The use of biomass as end-energy is plotted *vs.* time for the three consumption sectors electricity production, heating and cooling, and mobility. Data are taken from the German ministry of economy and energy.

because of the priority of food production —aggravated by the population growth— but also because of inroads into biodiversity with damages to fauna and flora already visible today. Because of environmental concerns over the extensive use of biomass for energy purposes —shrinking of biodiversity, over-fertilisation and eutrophication of inland waters and quality of drinking water, intensive use of pesticides leading to a reduction of insect population with the corollary on bird population, and lowering of carbon concentration in forest soil —the use of biomass stagnates in many countries. In addition, general concerns about the energy and CO₂ balance of some forms of bioenergy with doubts for a positive net energy output and a negative effect on CO₂ production along the whole live cycle are not yet removed in all cases [4]. Such a case is shown in fig. 7 for Germany. Plotted are end-energies from biomass for the three energy sectors: electricity, heating and cooling, and mobility, respectively. The biomass use saturates in all three sectors.

As bioenergy is mostly gained from crops like corn and rapeseeds on one hand and wood and organic waste from forests on the other, a rough measure of the national exploitation level is the primary biomass energy produced in a country divided by the areas of forests or those for agriculture use, respectively. Figure 8 shows this ratio for selected European countries both for the total biomass primary energy divided by the sum of forest and agricultural areas and separately for gaseous and liquid biofuels divided by the respective agricultural areas. Germany is leading in both quantities. In most countries the use of bioenergy saturates like in Germany; only UK shows a continuous growth in bioenergy production capacity.

It can be doubted whether the growth of biomass in Germany for energy purposes can

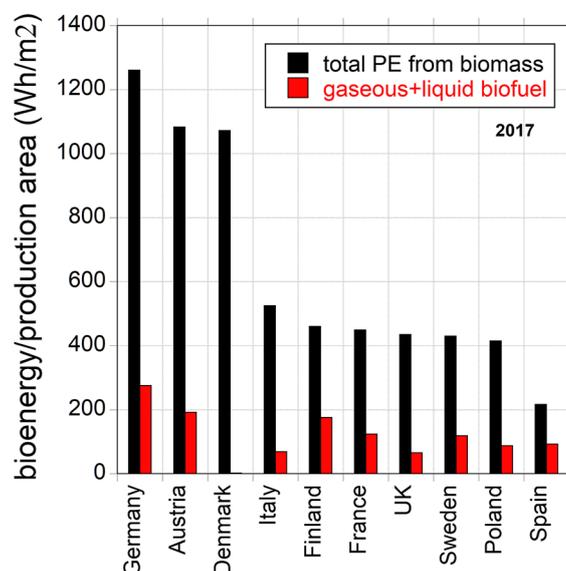


Fig. 8. – The ratio of total primary energy (PE) or gaseous and liquid biofuels, respectively, to the related production area is shown for various European countries for 2017. Data are from IEA and Index Mundi.

be increased beyond the present level. The exploitation potential seems to be reached. In the presence of an increasing population on Earth it has to be expected that arable land will be used more to feed people and animals in the future rather than producing additional biomass for energy.

Geothermal and ocean wave energy will be used where local circumstances are favourable, but these technologies will not play a decisive role. Also the further extension of hydro-power is limited in Europe. Only solar- and wind power have the potential to be scaled to high power levels if space and finances are provided. With their dominant use, the primary energy form in the future is electricity and other forms like chemical and mechanical energy have to be generated by transformation. These two expandable technologies with world-wide application potential have, however, two grave limitations. Electricity is generated in intermittent form so that these systems do not deliver secured power and cannot meet the demand without storage or back-up systems. Another feature of these systems is the low power density necessitating large collection areas and a high consumption of materials. End of 2018, 53 GW of onshore wind power was distributed over nearly 30000 turbines in Germany. In highly populated regions like in Europe, the dilemma develops that more people need more energy but also reduce the available space for its generation. More than 1000 groups were formed in Germany to protest against the local deployment of further wind convertors.

The science and technology behind wind and solar electricity generation has been discussed in this summer school in detail. In these concluding remarks, I will touch a few aspect of system integration mostly using the example of Germany. Germany is a

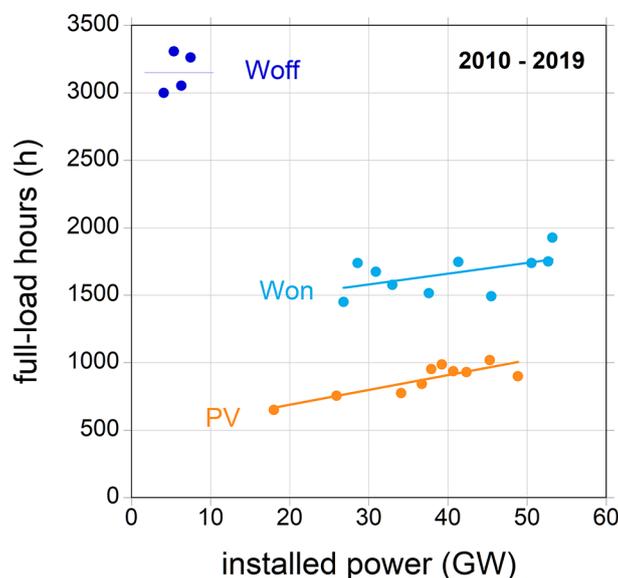


Fig. 9. – The full-load-hours (fh) are plotted for the three renewable energy forms onshore-, and offshore wind and photovoltaic power (PV) vs. the respective installed power. The last ten years are shown for onshore wind (Won) and PV; the last 4 years for offshore wind (Woff). The lines are fits in case of Won and PV and the average level in case of Woff. Data from ENTSO-E and the German grid operators.

good case to look at because of its high energy needs thanks to a high industrial level, its central position in the European electricity grid and its geographical location, which does not make it specifically suitable for the use of wind and solar power.

Low power density supply systems require larger areas and one major issue is the overall potential for placing wind convertors and PV panels. One has to discriminate between technical potential, which is an assessment of the specific technology requirements, *e.g.*, at what separation do wind convertors start to impair each other and the acceptable potential, which depends again in case of wind convertors on the compulsory distance to residential areas. The self-use of electricity from roof-top PV panels is financially attractive at high electricity costs even in low-sunlight countries like Germany. As the daily household demand profile does not fit to the supply profile the use of commercially available battery systems can well be considered. In conclusion, PV for individual supply is meaningful but is a good addition mostly for one-family houses. A meaningful use of large PV farms connected to the central grid can be questioned. The overall PV potential of Germany may be in the range of 300 GW. If this potential were to be used, a single grid would have to accommodate large power surges in the morning and large power losses a few hours later. During the night PV power is not available. But 42% of the German electricity demand accrues at times without direct solar support. Therefore, backup systems have to meet the demand during the nights

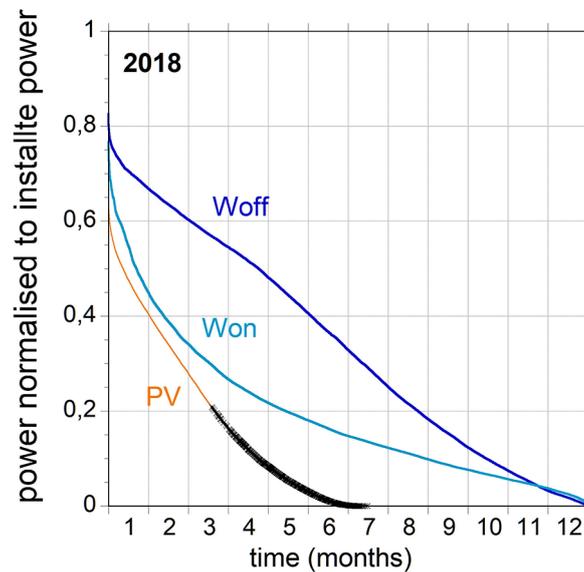


Fig. 10. – Annual duration curves for 2018 are shown for the three cases identified in fig. 9. The black PV symbols denote January and December values. Data from ENTSO-E and the German grid operators.

and they have to be able to cope with the large power swings introduced by PV. This scenario represents a tremendous challenge, which has to be successfully mastered every day unlike to the rare occurrence of an eclipse. The last one observed in Germany was March 20th, 2015 —which caused a strong variation of PV power giving rise to concerns regarding grid stability at a PV installation of then 40 GW.

Figure 9 shows the full-load hours, flh, of the three supply technologies under discussion. flh is the ratio of average power during a year to the installed power, $flh = \langle P \rangle / P_{inst}$. PV power shows the lowest value with a capacity factor lower than 12% offering a low harvest factor for the installed capacity. PV has intermittent electricity generation during a few hours a day only with additionally a strong seasonal variation. During December and January —periods of high demand— PV electricity production is only about 10% of the one during the summer months July and August. It can be doubted that a technical system with these basic features justifies the technical installations to cope with the challenging generation dynamics during the day and to develop the technology to save the surplus power. These conclusions apply to Germany but not necessarily to sunnier countries specifically when they additionally offer the possibility to generate hydrogen in systems isolated from the main grid.

Figure 10 shows the annual duration curves for the three systems we consider here. PV operates, of course, only half of the year. The black symbols denote January and December values from 2018. In the average, the daylight contribution in these months is 5% of the installed power.

In case of wind the flh values are higher than those of PV, for onshore wind by a factor of 1.8 and for offshore wind by more than a factor of 3. These factors denote the respectively higher energy production for the same installed power. Of course, offshore wind is more expensive per kW than onshore and PV power. But also offshore wind production suffers from extended lull periods with low production. In case of 2018, onshore (offshore) wind power in Germany was below 10% of the installed power for 2973 h (1853 h). The onshore-offshore wind correlation coefficient is 0.62. The consequence is that for about 1300 h, the lull periods overlap. The longest overlapping lull period lasted for close to 7 days.

The actual goals of energy production by REs are not to only meet the electricity demand proper but also to cover the other energy demanding sectors —heat and mobility. We will stay with the German energy situation to portray the possibilities and limitations in meeting the total energy demand. The national production potential of Germany is about 800–1000 TWh electricity by wind and PV power. The year-to-year variation is about $\pm 15\%$. In addition, 250 TWh from biomass may be possible. The sum is much below the present end energy use of about 2500 TWh, not to speak about 3700 TWh primary energy consumption. In case the electrical demand proper stays at the present level of 520 TWh a year, about 450 TWh electricity remain for other purposes. The German chemical industry has recently claimed an annual electrical demand of 600 TWh after the transition to fully de-carbonised processes; transportation by electric cars will need about 200 TWh in case of unchanged mobility. The German expectation that the electricity demand will decrease —a guide-line of German energy politics— is unrealistic facing the additional needs for digitisation of all possible operations, for automated processes using artificial intelligence, for the spreading of heat pumps, the development of “industry 4.0”, for the expectations in smart homes, smart grids and smart cities. All these developments will need more electricity. Even when the “Energiewende” is completed in 2050, Germany will remain an importer of energy like in the past. This is of European interest because the first question is, whether the neighbouring countries of Germany —as I consider this country as representative also for the generation limits of other northern European countries— will be able to help. This will not be possible if the neighbouring countries also resort to REs because of the high correlation of wind and PV production over Europe [5].

Figure 11 compares the onshore wind power of Germany with the summed-up onshore wind power of some of its neighbours (DK, PL, CZ, FR, BE, NL). The data show three weeks from January 2nd to 22nd, 2017. The high correlation both during lull and windy periods is clearly visible. The correlation coefficient between onshore wind power of Germany and summed up onshore wind power of its neighbours (no data from LU and CH) is 0.85 using data from the whole year. The summing up of the individual powers gives rise to a visible smoothing of the net power [6]. The coefficient of variation drops from the German value of 0.81 down to 0.53. Only the correlation between Germany and Austria is weak with a correlation coefficient of 0.29. The weather pattern at the location of wind parks in Austria differs from the one prevailing over northern Europe and is correlated with that of south European countries. Nevertheless, the consequence

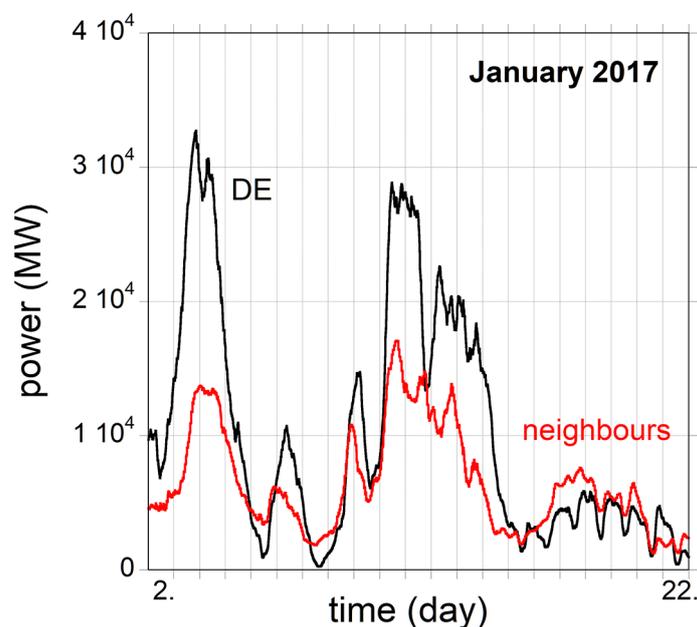


Fig. 11. – This figure compares the onshore wind power for Germany with the one of some of its neighbours (DK, PL, CZ, FR, BE, NL) for the period January 2nd to 22nd, 2017. Data from ENTSO-E and the German grid operators.

of this correlation is that neighbour countries will not so easily be able to help with their own wind generated electricity in periods where Germany is in need. When Germany cannot meet its demand, also her neighbours are in need.

Which conclusions can be drawn from the basic characteristics of weather-dependent electricity supply? At the present electricity costs, PV electricity makes sense for ones own consumption with roof-top PV panels. Open space PV arrays at the latitude of Germany do not seem particularly suitable due to the day-night variation and the practical failure in winter. Therefore, it is questionable to me whether this technology with a capacity factor of about 12% is worth the efforts to enlarge and enforce the grid to handle the daily power excursions or to invest into seasonal storage. One may have understanding for the local resistance against wind turbines, because the local landscape is seriously affected. Focus should therefore be on the targeted expansion of offshore wind as a European project. In my opinion, offshore wind should be an important pillar of future power supply. But the generation of electricity from wind and sun needs a storage solution for peak production. Storage in batteries is expensive because storage is in the form of electricity proper. Storage in the form of hydrogen causes larger transformation losses but the storage of the chemical medium itself is comparatively cheap. The decision in favor of wind and solar electricity production is inevitably also one for the entry into hydrogen technology to best make use of surplus production. The separate generation of

hydrogen *e.g.* via offshore wind should be considered in order to avoid oversized grids. A further chemical conversion of hydrogen into higher energy-density products can be considered as second step.

As far as import energy is concerned, the lion's share will not arrive in the form of electricity. The correlation between wind and PV generation will not allow this from neighboring countries to the extent necessary. Energy generation for import will come from wind and sun rich countries in the form of hydrogen or higher quality hydrocarbons. With the experience of building power lines from Thuringia to Bavaria, it is inconceivable that other countries will accept the large grids to pass through large amounts of electricity from the Maghreb countries to Germany. Hydrogen as the first transformation step beyond electricity will play a dominant role both to handle local surplus electricity and for the import of energy. Therefore, an exclusive concentration on battery driven electric vehicles seems to be unfavorable.

Decisions relating to Germany only are largely insignificant for the development of global warming, because a country alone cannot "save the climate". It must be in our own interest that technologies are developed, which remove fossil fuels out of the market and which are acceptable under the conditions of Third World countries. This is not the guideline for the Germany energy strategy as described above using the example of CCS technology or new fission reactor concept developments. Research is also necessary with regard to the future import of "green energy" in order to provide potential suppliers of green energy with the necessary concepts and technologies. Green energy does not flow out of the ground like oil and gas do rather has to be produced locally from renewable energies using sophisticated technologies.

The dimensions of the energy transition toward exclusively renewable energies are formidable and —I am afraid— not internalized in all aspects. After more than a decade of unprecedented development, 53 GW onshore-, 6.4 GW offshore-wind and 46 GW PV power contributed to the electricity supply of Germany end of 2018. These installations have to be expanded up to the national potential limit, which I can only roughly quantify for the three mentioned techniques with 200 GW, 85 GW and 300 GW. *E.g.* the onshore wind contribution has to be increased by about a factor of 4. Assuming linear development, the number of wind turbines would increase to 120000. It is questionable whether higher plant capacities will noticeably reduce this number, since increasingly less wind-prone locations must be included. The full utilization of the national potential by 2050 requires an annual expansion of 5 GW onshore-, 2.5 GW offshore-wind and 8.5 GW PV. Such peak values have so far only been achieved in one year —5 GW onshore wind in 2017, 2.3 GW offshore wind in 2015 or 8 GW PV in 2012, respectively. In the average, the per-year build-up values are 3.2 GW (onshore, over the last 10 years), 1.2 GW (offshore, over the last 5 years) and 3.9 GW (PV, 10 years). In addition to the replacement investments, Germany has to keep building these plants for 30 years at the top rates met, up to now, for one year only.

It can be expected that the future energy supply needs new technologies at large scale. Saving of energy will be the mission for the energy-rich countries but can hardly be expected for the majority of people on Earth. It was the mission of this summer school

and its proceedings to introduce into the most important technology concepts expected to supply mankind with energy for this century and beyond.

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