Structural deficits in research with respect to the challenge of the “Energiewende”

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Introduction

The “Energiewende” (energy transition) is, according to the definition on Wikipedia [1] the planned transition from unsustainable use of fossil energy sources and nuclear energy (through nuclear fission) towards a sustainable energy supply by means of renewable forms of energy. The Federal Republic of Germany is striving for the “Energiewende”, concerning in particular the expansion of wind and photovoltaic energy production as part of the sustainable energy supply. Thereby, it is easily overlooked that electricity production accounts for only a small part of primary energy consumption of the energy content of all energy sources used in Germany. If we look at final energy consumption by energy carrier, we have to distinguish between coal, fuels, heating oil, gas, electricity, district heating and other energy carriers, such as firewood, fuel peat, sewage sludge, garbage, etc. The share of electricity in final energy consumption in Germany amounted to only approx. 20 % for the year 2019 [2].

Should it be possible to completely replace electricity generation in Germany with renewable energy sources such as wind energy, photovoltaic energy, hydropower, biomass, etc., only one fifth of final energy consumption would have been produced sustainably. The “Energiewende” would thus still be far from being completed. Thus, at the present time it would be more accurate to speak of the “Stromwende” (electricity transition). The “Stromwende” can be viewed from various angles, such as the reliability of the power plants in the event of an accident, the procurement of the energy carrier for their operation, the acceptance by the population, and waste disposal. An evaluation and weighting of these aspects is ultimately a task for society and thus, for the politics. Different countries arrive at very different results in this respect. In the following, the power supply is considered exclusively from the point of view of security of supply and low CO_2 emissions.

Challenge “Stromwende”

Load profile of electricity production of an industrialised country

Electricity consumption in an industrialised country is made up of a constant and a fluctuating share. For the fluctuating part, there are different time scales involved. There is a diurnal variation, i.e. more electricity is consumed at midday than during the night. In the course of a week, more electricity is consumed on weekdays than on weekends, because industrial production takes place mainly during the working days. And finally, the annual cycle should be mentioned, i.e. more electricity is consumed in winter than in summer. The annual electricity demand therefore has its maximum around midday on a working day in January.

Irrespective of the fluctuating share of electricity consumption, there is a constant component, which in Germany is about half of the maximum consumption. The base load is therefore the lowest daily load of an electricity grid. It follows from this that a continuous minimum power generation is necessary. The aspect of base-load capability of an energy carrier is of particular importance for the security of electricity supply. Base-load capable are those energy sources that can constantly supply the lowest daily output. Nuclear power plants can produce electricity independently of the sun and the wind and are base-load capable. On the other hand, they can only react to short-term peaks in electricity consumption to a limited extent [3]. Gas-fired power plants are suitable for this, as they can be brought up to full load in less than half an hour. Pumped-storage power plants have an even faster load-following capacity, as they can ramp up their output within one minute.[1] With both the last two energy carriers, reduced power feeds from wind and photovoltaic plants can be compensated on a short time scale.

Security of power supply

For the security of supply of electricity production, it must be guaranteed that the sum of the energy sources is always able to match the generation of electricity consumption. Power generator are particularly important in this respect, which, apart from maintenance intervals, can feed energy into the grid at any time. Wind and photovoltaic energy are volatile forms of energy that are not continuously available. With exclusively renewable forms of energy, a reliable power supply can only be guaranteed if the overproduced energy is stored temporarily and then fed into the grid during the night or when there is a lull in the wind. Such "dark doldrums" are periods in which neither the sun shines nor the wind blows. One must take into account the fact that weather conditions can occur in Europe where there is little wind for many days. For such periods, large amounts of energy would have to be stored temporarily. Corresponding storage technologies that could be operated economically are not yet available. Unfortunately, storage by pumped-storage power plants on the scale required is out of the question for Germany. It does not have enough mountainous terrain due to its topography.

If it should not be possible to cover the demand for electricity during periods of low production, the alternative would be to selectively disconnect electricity consumers (grid load) from the grid in order to avoid a collapse of the power grid – a so-called "blackout". Storing electrical energy in the power grid itself is not possible. The electrical energy fed into and withdrawn from the grid must always be in equilibrium. In addition, the problem arises that when "excess" energy is fed into the grid, the grid frequency of 50 Hz could not be kept stable. It would inevitably lead to an increase in the grid frequency ("overfrequency"), which in turn would cause damage to various consumers.

Since a future energy supply must be low in CO_2 emissions in order to counter the anthropogenic greenhouse effect, the fossil energy sources can no longer be used in base-load operation as they have been in the past. This justifies the necessity of the "Energiewende", which has so far focused on the fastest possible expansion of renewable energy sources in Germany. At the same time, it is overlooked that the energy concept still has major gaps in terms of security of supply [5]. Alternative long-term storage for energy from wind and photovoltaic energy is not yet conceived in the required order of magnitude. There is therefore, a need for research in order to to develop and realise long-term storage facilities. Germany in particular, as one of the leading industrialised countries, has a responsibility in this regard with its research policy.

Concept of the "Energiewende" in Germany

Instead of investing broadly and substantially in energy research over many years, since the levy of the Renewable Energy Sources Act (EEG) in 1991, the expansion of photovoltaic energy and wind energy has been pushed. However, it was ignored that these energy carriers also have their disadvantages. After the end of their maximum operating life, photovoltaic systems are electrical waste that must be disposed of properly. The rotor blades of wind turbines are also difficult to recycle, as they are made of composite materials, including rare balsa wood. In addition, birds and bats are killed by the rotor blades and in winter there is a risk of ice being thrown in the vicinity of wind turbines, with potentially fatal consequences. Probably the most serious disadvantage of

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[1] Unfortunately, the pumped storage capacity available in Germany of around 7 gigawatts (GW) is relatively low and provides per cycle only 4–8 hours of continuous operation [4].

energy generation by wind and photovoltaic energy is that the achievable power densities are very low in contrast to conventional power plants[2]. As a result both forms of energy have a significant consumption of land and materials[3], as significant revenues can only be generated on large areas.

Prior the reactor accident in Fukushima, Japan, Germany had an energy concept [8] for power generation, which consisted of the following components: firstly, wind and photovoltaic energy as regenerative forms of energy, secondly, energy from nuclear fission to cover the base load, and thirdly, gas turbine power plants with fast response reaction time to compensate for weather-related reductions in the output of the renewable forms of energy. The predominant share should be provided by wind and photovoltaic energy. The complementary properties of wind and photovoltaic energy on the one hand and nuclear fission on the other hand, were well suited to provide a reliable and low CO_2-emission power supply.

Although the operating times of nuclear power plants were extended shortly before the Fukushima reactor accident – nuclear energy was described as a "bridging technology" – the German government decided in 2011 to phase out nuclear fission in Germany. The inherent risks of nuclear fission, i.e. the potential danger of a reactor core meltdown and the unsolved problem of disposing of the long-lived radioactive isotopes of the nuclear waste were cited as reasons for this decision. In addition, there is the problem of proliferation, i.e. the passing on of weapons-grade fissile material, which is directly linked to the peaceful use of nuclear energy through nuclear fission.

Due to the gradual shutdown of nuclear power stations and the future shutdown of coal-fired power plants, the need has arisen to fill the resulting gap in the energy supply. It must be noted that the capacity that is now being shut down was previously provided by power plants which were capable of supplying base load. Another aggravating factor is that a significant increase in electricity consumption is forecast for the coming years [9]. Two driving factors are the planned expansion of electromobility and the further progress of digitalisation[4] of society.

Current data on the "Energiewende"

In 2020, the output of the wind turbines installed in Germany on land was $P_{\text{won}} = 54.4$ GW and at sea $P_{\text{woff}} = 7.75$ GW. On land about 103.7 terawatt hours (TWh) and at sea around 27.3 TWh of energy was generated, i.e. a total of around 131 TWh [10]. If we now compare the energy that could theoretically be generated over a year with the installed capacity at full load with the energy actually generated, the following capacity factors (annual utilisation rates) are obtained for the wind turbines: 103.7 TWh / (54.4 GW · 8784 h) = 22 % on land, 27.3 TWh / (7.75 GW · 8784 h) = 40 % at sea, for a combined total of 131 TWh / (62.15 GW · 8784 h) = 24 %. It can be seen immediately that the offshore wind turbines have a better annual efficiency by a factor of two. This is due to the fact that the wind blows more constantly and at a higher speed at sea than on land. The wind power increases with the third power of the wind speed [11], which is why the selection of a "windy" site is important for the successful use of a wind turbine.

In 2020, the output of the photovoltaic systems installed in Germany amounted to $P_{\text{pv}} = 53.7$ GW and around 48.6 TWh were generated [12]. If one calculates the annual utilisation rate of the photovoltaic systems, the result is: 48.6 TWh / (53.7 GW · 8784 h) = 10 %. The annual

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[2] The power that can be achieved with one square meter of photovoltaic system in Germany is about 20 W; the output of wind turbines per square meter is 1.1 W–6.7 W and depends strongly on the shading of the wind turbines in the wind farms [6]. Here, shading means that the wind turbines extract energy from the wind and as a result neighbouring wind turbines can generate less energy.

[3] A wind turbine with a typical capacity of 3.2 megawatts (MW) in 2020, operating at sea, i.e. "offshore", will require approximately 26 t of copper [7].

[4] This includes the use of streaming services and cryptocurrencies. The latter have to be mined with a high energy input.

utilisation rate of the photovoltaic systems is very low at only 10 %.[5] The reasons for this are the outage during the night, shading due to cloudiness and the geographical location. The location of the photovoltaic system is therefore important. Photovoltaic systems should preferably be installed in "sunnier" locations, i.e. where the solar irradiation per square metre and year is particularly high, e.g. in North Africa.

If one adds up the energy production from wind and photovoltaic plants, it shows that in 2020 (132 TWh + 48.6 TWh)/567 TWh = 32 % of the electricity produced [13] came from wind and photovoltaic energy. Let us assume that the share of electricity in final energy consumption of approx. 20 % in 2019 can also be assumed for 2020, this results in a share of 32 % · 20 % = 6 % of wind and photovoltaic energy in Germany's final energy consumption. Conversely, this means that in the year 2020, approx. 94 % of final energy consumption will not come from the two cornerstones of the German "Energiewende" – wind and photovoltaic energy. In the same year, 30.9 billion euros [14] flowed to the operators of wind, photovoltaic and biomass plants [15]. Of the total EEG remuneration[6] 34.5 billion euros were generated by 41 % wind energy (onshore and offshore), 34 % by photovoltaic energy (solar radiation energy) and 23 % by biomass [16].

Critical remarks on the "Stromwende"

Since wind turbines and photovoltaic plants have been in operation in Germany for years, long-term data on their yields are available. This data can be used to model different scenarios. The following results are taken from a publication by F. Wagner [17]. Assuming that the electrical energy consumption of the years 2010–2015 had to be covered by wind turbines and photovoltaic plants to 100 % , the optimal mix[7] would be as follows: $P_{\text{won}} = 174$ GW, $P_{\text{woff}} = 43$ GW, and $P_{\text{pv}} = 118$ GW. It would therefore have been a total output of 335 GW of renewable energy forms to be installed. This is four times the maximum load of electricity consumption. In addition, it would have been necessary to maintain a reserve capacity of 73 GW of conventional power plants in order to produce only 132 TWh in periods of shortage and during dark doldrums. The reserve power plants would thus have a annual utilisation rate of only 132 TWh / (73 GW · 8760 h) = 21 % – far too low an annual utilisation rate to enable an economically viable operation of power plants.

Another important aspect is the distribution of the electricity produced from the wind turbines, which are located in particular in the North of Germany. For this purpose, so-called "electricity highways" are needed, i.e. high-voltage direct-current transmission lines to transport the electricity to the consumers in the South. Unfortunately, there are significant delays in the expansion of these lines.

For a fair comparison of electricity production costs, the costs of providing the reserve power plants must be added to the electricity production costs of the renewable energy sources. This also applies to the costs incurred if wind turbines have to be shut down due to massive electricity overproduction, or if sales prices collapse. The sales prices for electricity can even turn negative, i.e. the electricity sellers have to pay a compensation. This happens when supply exceeds demand. In such phases Germany's neighbouring countries are not prepared to buy any amount of energy in the form of electricity, as they fear a destabilisation of their own electricity grids. Poland and the Czech

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[5] This is roughly equivalent to the energy generated by five medium-sized nuclear power plants with a nominal output of about 1.4 GW and an annual efficiency of 90 %.

[6] Total of remuneration and premium payments without completed plants pursuant to § 21 (1) No. 3b EEG as well as income from the marketing of electricity quantities in accordance with § 20 EEG (market premium)

[7] The optimal mix of wind and photovoltaic energy is defined by a minimum amount of reserve and backup energy needed during the year, in case weather conditions do not allow intermittent renewable energy sources to meet demand.

Republic, for example, have installed phase-shifting transformers to block the "overproduction" of electricity from Germany at the border [18].

The above model calculation shows the basic problem of the volatility of renewable forms of energy, i.e. the circumstance that they are not continuously available. There are moments of overproduction as well as moments of undersupply, in which the reserve power plants, which are only poorly utilised on average, have to step in. If one does not want to resort to a backup structure of power plants with fossil energy carriers or nuclear power plants, it is indispensable, to have storage facilities for wind and photovoltaic energy. It is important that a consistent overall concept is developed, in which the optimal mix of the various renewable energy sources is sought.

Whether the power-to-gas technology – production of fuel gas using an electric current [19] – will be able to act as an energy storage will depend on the efficiency that can be achieved and whether it will be possible to carry out the processes in the required scale. Corresponding technologies do not yet exist.

Critical remarks on the "Energiewende"

The realisation of the "Energiewende" is very ambitious, since the total volume of energy production in modern industrial societies is large (electricity generation alone in Germany amounts to 567 TWh [13] in the year 2020) and since it implies replacing of current energy production by renewable energy sources within a period of 20–30 years. Moreover, the "Energiewende" must be achieved on a global scale if we are to sustainably reduce human-induced global warming. The political challenges are enormous, since worldwide, in a concerted effort over several decades, the political framework conditions for the "Energiewende" need to be in order to guarantee planning security.

The "Energiewende" envisaged in Germany will require considerable resource consumption of raw materials [7], thus it will not be possible to scale up to the entire world. The "Energiewende" is a particular solution for rich industrialised countries that can afford it financially. In order to make the "Energiewende" a model of success for the entire world, a much broader concept is needed, which in particular includes energy saving through renunciation (sufficiency), increased efficiency and innovations at the centre. In general, therefore, the "Energiewende" must be flanked by large-scale research efforts if it is to be a success. For example, nuclear fusion also has the potential in principle, to close a substantial part of the energy gap, but it is still in the development phase.

A global endeavour of comparable magnitude has not yet been successfully completed by mankind, although similar global challenges have existed for centuries, such as the fight against hunger and poverty. It should also be noted that disruptive political events[8] manifest themselves on medium time scales, which can change the focus of political action and the associated money flows within a short period of time. For Germany in the past fifteen years, the following events occurred: the financial crisis, the refugee crisis, the COVID 19 pandemic and the Ukraine crisis. The COVID-19 pandemic, in particular, once again showed how difficult it is on transnational level to ensure coordinated action under crisis conditions.

In the case of global warming, the situation is aggravated by the fact that the time scales involved amount to several decades, i.e. that a drastic CO_2 reduction would have no immediate effect on anthropogenic global warming. Instead, global warming would continue to progress. It is difficult to convince society that the measures taken and the associated restrictions on the living standards of many people should be for many years without any visible effect.

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[8] These are the so-called "black swans", because the occurrence of these events cannot be predicted by extrapolating developments [20].

Structures and time scales in science

In a roadmap, the International Energy Agency (IAE) describes a scenario that should lead to zero net CO_2 emissions by the year 2050. In this scenario, about half the annual savings in CO_2 emissions is based on technologies yet to be developed [21]. The fundamental question is whether science, with its current structures, is in a position to meet the high expectations placed on it with regard to the realisation of the "Energiewende" in a timely manner. It is not only a question of additional financial and human resources that need to be made available in the context of the "Energiewende" but also about the time scales that prevail in basic research. In basic research it is usual to have to "sow" decades before one can "harvest" scientific successes because the creativity necessary in science cannot be accelerated at will.

The large time scales on which scientific progress is made conflict with the fact that the global "Energiewende" must be completed in 20–30 years if global warming is to be limited to two degrees Celsius. Moreover, many politicians are probably unfamiliar with these large time scales, since in the meantime, political planing to be made at most a few years in advance. Nevertheless, it is the task of politics to establish the long-term framework conditions for science accordingly, so that science can make its essential contribution to the "Energiewende".

It should be ensured that the necessary number of scientists can be trained and recruited. It should be borne in mind that the training of a scientist takes about 10 years (5 years to complete a master's degree, 3 years for a doctorate and 2 years for a post-doctoral phase). Compared to the "Energiewende" with its envisaged time horizon of 20–30 years, this is already quite a long period. It is therefore necessary to take countermeasures in good time here, so that the realisation of the "Energiewende" does not fail to a shortage of well-trained scientists.

Executives in science under constant stress

The higher the reputation of a scientific leader, the more he or she will be offered to get involved in scientific bodies and committees. This often goes hand in hand with increased reviewer activity. As a result, there is an "accumulation of duties", which cannot be adequately managed even with a high workload and a high degree of intensification of work. Correspondingly inadequately prepared members sit on the scientific bodies and committees, who have to try to do justice to their task with a minimum of effort. This is unfortunate, since it is in the scientific bodies and committees that the course for research projects and research policy is set.

Until the COVID 19 pandemic, it was common for most meetings to be held in person, which entailed a lot of travel. Business trips do not provide ideal conditions to concentrate and lead to exhaustion when they occur frequently. In addition, the executives are not available at the place of work to hold discussions with staff and to supervise junior academic staff.

Furthermore, the executives are confronted with frequent evaluations of their departments or institutes, which are very time-consuming. The result of the evaluations is often not very meaningful, since they essentially evaluate how well they present their research activities and how well they are socially networked in their research environment. In energy research, a trend can also be observed, whereby the evaluation is carried out with the aim of checking conformity with the political agenda. Evaluations are also often accompanied by explicit demands for the preparation of timetables detailing the research goals to be achieved in the future. This is fundamentally questionable, since many achievements in research have a disruptive character and are therefore fundamentally unpredictable.

In principle, researchers should be intrinsically motivated and high-performing. Then, steering structures can be reduced to a minimum. The guiding principle must therefore be to develop as early and as thoroughly as possible the willingness and ability of the prospective researchers and then to let them do their research as independently as possible. As a rule, the researchers themselves know best how to make their research efficient, not the politicians. One must not make the mistake of organising research according to business considerations in order to establish tight controls. Research is not about creating a shareholder value within a manageable time horizon, but rather to create an environment in which the creativity of the researcher can flourish, so that scientific progress can be achieved on medium to large time scales. This is better achieved with trust than with counterproductive controls.

In the academic environment, executives are expected to raise a significant amount of third-party funding, the proper use of which is subsequently monitored. Writing research proposals is time-consuming and unfortunately often unsuccessful [22]. The quality of a leader is not only judged by his/her research performance but also on the ability to raise substantial funding per year. The support of (basic) research by means of solid funding has been discredited as inefficient over the past decades, since it also feeds researchers who are unwilling to perform. This criticism falls short, because it ignores the fact that the majority of researchers are intrinsically motivated and need external control only to a very limited extent. It is therefore counterproductive that the willing and able researchers have to spend a large part of their time attracting third-party funding instead of devoting it to research itself. For this reason, it is desirable that at least 2/3 of basic research to be financed by basic funding.

Science is generally not isolated from social developments. For example, the legislator is enacting more and more regulations in order to impose socio-political ideas in the companies and thus, also in the research institutions. Although “noble” goals are aimed at in this way, the practical implementation of the regulations leads to an additional workload for executives. Correspondingly less time is left for the actual research work.

The flood of e-mails also hits executives particularly hard, as they are on many e-mail lists.[9] As a result, the executives are constantly reading and answering e-mails, as they are always under pressure to be permanently available.[10]

Since many academic executives are professors and thus, *per se* involved in the education of undergraduates and doctoral students, it would be desirable to make scientific teaching more efficient. A step in this direction could be the increased recruitment of lecturers at the universities, who would, equipped with permanent positions, devote themselves to teaching the basics in the subsidiary subjects, such as introductory mathematics lectures. Instead, the professors should devote themselves to lecture in the core and advanced subjects, in order to ensure the topicality of the academic education and to maintain contact with the students. However, it would be more efficient if lecturers could hold the basic lectures, in order to conduct them at a high didactic level.[11]

As a rule, advancement to the position of leader in an academic environment is associated with a significant reduction in one’s own scientific research activities. In many cases, it even means saying farewell to it. Instead, the focus is on managing science and scientists. This is tragic insofar as scientists who have excelled in the fierce competition and reached the top, can only actively contribute to research to a limited extent. As there are fewer and fewer permanent mid-level

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[9] This is exacerbated by the bad practice of replying in general to the entire mailing list listed under “CC”, even if the reply is intended only for the author.

[10] For example, during presentations at conferences and seminars, many of the participants answer their e-mail instead of listening to the speaker. Unfortunately, there is the misconception that one can both follow the presentation and answer the e-mail.

[11] In addition, a national canon of basic lectures should be introduced which can be accessed digitally by every student. Here it would be advantageous if scientific didactics could contribute to the creation of these lectures. All students would then have an alternative digital access to high-quality basic lectures.

academic appointments – this is particularly true for universities – active scientific research thus rests essentially on the shoulders of the postdocs, who usually also supervise the doctoral students scientifically.

The goal must be to give top researchers more time for their core tasks – research and teaching. Evaluations should be reduced to a minimum, and administration should see its primary task in supporting and relieving the executives. In addition, politics should be limited to setting the broad lines of research policy. The detailed implementation is then the task of the executives in the research institutions and universities. Only these have the necessary detailed knowledge to ensure efficient implementation.

Fix-term appointments in research

Temporary employment contracts in science have become the norm in recent years. This has happened despite the Temporary Employment Contracts Act (WissZeitVG), which was supposed to counteract this development, but failed since simultaneously, permanent employment contracts have been massively reduced. Subtracting doctoral students, almost eighty per cent of academic staff at universities works on fixed-term contracts [23]. Such scandalous conditions have ultimately become widely accepted normality. As far as the Max Planck Society is concerned, an "MPIfG Discussion Paper" [24] is devoted in detail to this deplorable state of affairs. Those affected themselves come forward, for example, under the hashtag #IamHanna on Twitter.

As we have seen in the previous section, due to the time constraints of the scientific leadership, a large part of the research is on the shoulders of postdoctoral researchers. Their efficiency is diminished by the fixed-term employment contracts, which typically last only two or three years. The postdocs are thus permanently occupied with moving from one fixed-term position to the next. Each change of position brings with it a period of familiarisation. A longer-term work on a project or a scientific advance is therefore difficult to realise. Many postdocs therefore confine themselves to scientific questions that seem promising to yield results within a short period of time, in order to convince the employer to extend the temporary contract before it expires. The focus is thus not on thorough scientific work on long-term projects, but rather the maximising the number of publications. The struggle for the next temporary position often leads to a climate of competition among postdocs. In a scientific environment, cooperation should be in the foreground.

The widespread abolition of the academic mid-level faculty at the universities, but also at research institutions, was a big mistake. The former mid-level faculty, with their permanent employment contracts was a guarantor of continuity in the academic field and repository of the traditional detailed knowledge within the research groups. It led to a reduction in the workload of the executives in training young scientists and made it possible to pursue long-term research goals. It must once again be the goal of universities and scientific institutions to give talented employees a permanent perspective in the academic environment after successful evaluation. Instead, an academic precariat has emerged that is not protected from exploitation and whose members move around the world as migrant workers. As a consequence, many talented scientists leave their academic careers early out of frustration with the existing conditions. The economy benefits from this trend because it can recruit employees with a high level of academic education and intellectual skills. It has to be said that, because of the poor career prospects in academia, it is in no way guaranteed, that the greatest talents will remain in science.

Time scales in basic research

In society, and especially in politics, there is a lack of understanding of the time scales on which scientific change takes place. When it comes to the really difficult problems in the natural sciences and in technology, they are usually only solvable on time scales of several decades. If one compares this with the ascent of Mount Everest, several stages with camps are necessary to complete the ascent. In the process several generations of scientists are necessary, each building on the knowledge and preceding work of the previous generation. This insight is summed up in the parable of the "dwarfs on the shoulders of giants" [25]. Even if it is not possible for a scientist to reach the top of the mountain, one can nevertheless, make a necessary contribution so that future generations of scientists succeed in doing so. Unfortunately, perseverance and patience are rare commodities in our fast-moving times. For the young generation of scientists, the path to the summit becomes correspondingly more difficult as it gets longer and longer.

It is therefore imperative that continuous funding of science be ensured and that this, as justified above, be achieved to a considerable extent by means of solid basic funding. Only then the conditions are created for addressing the difficult and important questions in science that guarantee scientific progress. Two particularly examples of this are the development of the lithium-ion battery and that of the white luminescent LED, the development of which took several decades and was achieved by several generations of scientists. Without the lithium-ion battery, electromobility would hardly be conceivable and without the white LED there would be no economical LED lamps. Both are good examples of how the funding of basic research can pay off for society over a long period of time. It is therefore pure wishful thinking that the technical prerequisites for a conversion of the energy supply to sustainability can be created within a few years. Large-scale energy storage technologies have a research backlog of many years and should have been massively supported by research projects, preferably in parallel.

Nuclear fusion is a prime example of a highly complex research subject that can only be translated into a technical application on a time scale of 100 years of research, but which promises considerable benefits. It has the potential to make a significant contribution to the energy mix in the future, since, like nuclear fission, it produces low CO_2 emissions, has a high-power density and can be used in base-load operation. In addition, nuclear fusion has the advantage that by design it does not lead to a meltdown and only produces radioactive waste with a comparatively short half-life. Curiously, the research into nuclear fusion, which has been going on for 70 years now, is being seen critically from various sides, yet despite the great progress that has been made in this field [26, 27].

Since the switch to renewable energy sources will have to take place within the next 20–30 years in order to limit global warming to two degrees, the argument has recently been put forward that nuclear fusion, should it be realised, would ultimately be too late. This argument is flawed, because one cannot conclude from the fact that something has been planned to occur in a well-defined time frame that it will actually happen. It is very questionable whether the "Energiewende" can be realised worldwide in time. A delay or failure would be conceivable for various reasons. In this case, a resurgence in the use of nuclear fission would be unavoidable, unless nuclear fusion were available as an alternative energy source. Moreover, should energy consumption continue to rise in the long term, despite efforts to save, we can consider ourselves lucky for every additional low CO_2-emission energy carrier that is ready for use.

Summary

The global “Energiewende” (energy transition) must be implemented for two important reasons. On the one hand, fossil fuels will only be available for a limited period of time, and on the other hand, their combustion leads to emissions of CO_2 and thus, to the anthropogenic greenhouse effect. Unfortunately, the “Energiewende” in Germany has three serious weaknesses at present. Firstly, the problem of storing energy from wind and photovoltaic energy has not yet been solved satisfactorily. Secondly, the “Energiewende” has so far focused on the electricity production and thus, on one fifth of total energy consumption only. The wind and photovoltaic energy together currently have a share of only 6 % of final energy consumption. Therefore, we are dealing with the “Stromwende” (electricity transition), which means that the dominant share of the “Energiewende”, despite considerable subsidies from the Renewable Energy Sources Act (EEG) over a period of 30 years, has not yet taken place. Thirdly, Germany’s CO_2 emissions in the year 2019 are only 1.8 % [28] globally, i.e. with the completion of the “Energiewende” in Germany, the global problem of the anthropogenic greenhouse effect is not even remotely solved. Only if the German “Energiewende” can be implemented on a global scale, can it serve as a blueprint. Whether this will succeed is doubtful, since the focus on wind and photovoltaic energy will result in a considerable consumption of raw materials, which cannot be financed globally. Therefore, there is still a pronounced need for research in order to develop the technical basis for the “Energiewende”.

The analysis of structures in the scientific community has shown that we are not well positioned to tackle the important research projects that are particularly needed in the course of the “Energiewende”. The scientific executives are chronically overburdened, the academic mid-level staff, who could ensure continuity, have fallen victim to cost-cutting measures in recent decades, and the postdocs, who are supposed to replace the mid-level staff, “shimmy” from one temporary contract to the next. One cannot expect the postdocs, with a typical time horizon of two to three years, to tackle difficult research topics long term in their temporary positions.

Fortunately, there are still a few scientists with temporary contracts who take on considerable professional risks and sacrifice a large part of their free time to get involved in difficult scientific problems in spite of the existing conditions. In quantitative terms, the increase in knowledge may well still occur but, whether the qualitative growth, which is associated with the capacity to solve of difficult to the most difficult scientific questions, must be critically evaluated. Nor should we fail to recognise that the science system has a great deal of temporal inertia, so that the deficits that have already built up only take effect with delay.

This is particularly worrying because we need to rely on science to transform our society towards sustainability. Unfortunately, there is a large part of society with the mistaken belief that the “Energiewende” is already technically feasible. This is not the case as long as the appropriate storage systems for the renewable forms of energy or alternative base-load power plants have been developed or implemented. In addition, the size of the time scales involved in basic research and its technical implementation is systematically underestimated by the political actors. In this context, due to the anthropogenic CO_2 emission, we are increasingly running out of time – time that would have been needed in the order of decades in basic research. Whether the “Energiewende” can be achieved in the given time horizon of 20–30 years remains questionable. Therefore, in addition to the regenerative energy sources, alternative energy concepts, such as nuclear fusion, must be further researched, even if just to have a plan B up our sleeve if necessary.

Closing remark

Unfortunately, the public perception is that society only needs to provide economic resources to install the necessary wind turbines and photovoltaic systems. The rest will be done by science and industry. In the process two things are overlooked:

On the one hand, scientists are not the “masters of the universe”. They can only read the book of creation, but they cannot rewrite it, because the laws of nature are non-negotiable. One can only accept this fact humbly. This may be difficult for society to understand, because it is in the social behaviour of man to negotiate, or to satisfy his demands by aggressive behaviour. One must understand the order of magnitude of the continuing increase in global energy consumption of approx. 480 Exajoule/year[12] in 2020 [29] to understand what a challenge it is for science and technology to satisfy this demand permanently. At the moment, we are only able to do this because humanity is overexploiting the earth’s resources and not because the appropriate technologies for sustainable energy production have already been developed.

On the other hand, it is overlooked that the “Energiewende“ will not be possible without a fundamental change in Western lifestyles. So far, any efficiency gains in energy production have been compensated or overcompensated by increased demands. Cars have become bigger and thus, heavier, the screen diagonals of televisions have steadily increased, the travel destinations have become more exotic[13] and the demand for living space per person is constantly growing. Many more examples can be given. As a result, global energy consumption continues to increase.

The actual problem is even more serious, since the reserves of raw materials are steadily diminishing and the global ecosystem is being systematically damaged. The “Energiewende” is thus only one aspect of a comprehensive sustainability debate. In the long term no way around closed resource cycles and sufficiency – a lower consumption of resources such as energy and materials. Whether this will succeed in socio-political terms is questionable. On the one hand, our financial system depends on an exponentially growing economy in order to generate interest. For another, Western society has become accustomed to a steady increase in prosperity. The prevailing motto is “anything goes” and not the self-determined restriction of consumption. The core problem is that the consequences of the global overexploitation of the earth’s resources only manifest themselves with great delay. We are already decades behind a general change of course. The tragedy is that it was not a lack of knowledge in the past that could justify it.

With the consequences of the anthropogenic greenhouse effect becoming visible, the public debate on the “Energiewende” is becoming increasingly emotional. This is regrettable, since the “Energiewende” is in need of social acceptance, but at its core it is a scientific problem. Its implementation should therefore be guided by rationality and not by moral arrogance. Ultimately, we need the cooperation of all societal forces to make the “Energiewende” a success.

The free version of DeepL Translate `https://www.deepl.com/translator` was used to translate the German text into English.

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[12] This is the 25 times the basal metabolic rate, i.e. the resting energy demand of all humans: $(480 \cdot 10^{18}\ \text{J/year})/(6.7\ \text{MJ/(day, human)}\ 365\ \text{day}\ 8 \cdot 10^{9}\ \text{human}) \approx 25$ with $6.7\ \text{MJ} \mathrel{\widehat{=}} 1\,600\ \text{kcal}$.

[13] Which recently also includes near space.

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