Study

Deutsche Physikalische Gesellschaft DPG

Electricity:
The key to a sustainable and climate-compatible energy system

A study by the Deutsche Physikalische Gesellschaft e. V.
(German Physical Society)

June 2010
(Translation December 2011)

Electricity:
The key to a sustainable and climate-compatible energy system

A Study by the Deutsche Physikalische Gesellschaft e. V.
(German Physical Society)

June 2010

(Translation December 2011)

Preface

The effects of the anthropogenic climate change pose some of the greatest challenges faced by our global civilisation. If carbon dioxide (CO_2) production during energy supply is not drastically reduced, there will be grave changes throughout the world. The introduction of a climate-responsible energy supply, therefore, is one of the “great challenges” of this century. The natural sciences, in particular, are required to search for effective solutions across national borders and scientific disciplines, develop them and bring them to fruition.

Accordingly, the German Physical Society (Deutsche Physikalische Gesellschaft, DPG) considers it its responsibility to examine the possibilities and prospects of avoiding CO_2 emission from energy generation and consumption. This study, “Electricity: The Key to a Sustainable and Climate-Compatible Energy System”, was conducted by the Working Group on Energy (Arbeitskreis Energie, AKE) of the DPG. With this study the DPG, as a scientific society, aims at providing a contribution to the discussion on climate and energy policies in the German and European contexts.

Climate-responsible energy supply is a complex interdisciplinary issue which cannot be solved by the methods and facts of physics alone. Knowledge of these facts and methods, however, is the indispensable basis of necessary political decision-making. This study focuses on this basis and, rather than making recommendations, attempts to present the spectrum of possible options and their physical background. A factual analysis of energy supply and utilisation was conducted with regard to the first half of the 21st century. Although this study makes no claim to completeness, it examines all major options in developing a carbon-lean energy system. In particular, it demonstrates that electric energy has been playing, and will continue to play, an increasingly important role in the interplay of the various forms of energy.

Fundamental physics plays the decisive role in determining the various technological options possible. Expertness, innovation, strategic thinking and perseverance are called for in order to successfully realise these options. The DPG will continue to provide its expertness in order to meet these great societal challenges.

Wolfgang Sandner

President of the
German Physical Society

Martin Keilhacker

Chairman of the
Working Group on Energy of the
German Physical Society

Gerd Litfin

Vice-President of the
German Physical Society

Eberhard Umbach

Former President of the
German Physical Society

Table of Contents

Summary

Climate change with its potentially serious dangers to mankind requires restructuring of the world's energy supply for the purpose of drastically reducing CO_2 emission. This study presents an overview of present electricity utilisation and a forecast of the role electricity could play in a modern society such as Germany's that is intent on CO_2 avoidance during energy generation and consumption. There are many indications that the importance of electricity in the interplay between the various forms of energy will continue to increase in the coming decades.

Generally speaking, this study takes as its starting point the state of affairs presented in the German Physical Society's 2005 publication "Climate Protection and Energy Supply in Germany 1990-2020 ("Klimaschutz und Energieversorgung in Deutschland 1990-2020") and examines the general situation in Germany up until about 2030. Where appropriate, the situation is presented in the wider context of the European Union or, indeed, the world, and the time horizon is extended to about 2050. However, this study makes no claim to being a complete analysis that devotes equal attention to all possible issues, but rather seeks to highlight those aspects that are of particular importance to the future development and to address issues that may benefit from considering a change of direction or priorities.

This study is divided into three parts: utilisation, supply and distribution of electric energy. It concludes with an outlook on the role of electricity in a future sustainable and climate-compatible energy system.

1 Utilisation of electric energy

Utilisation sectors –
Electricity demand is going to increase

The share of electricity in Germany's end-use energy consumption is currently about 22%. It is statistically recorded by utilisation sectors. The largest consumer is the industrial sector (43%), followed by private households and the business, trade, and services (BTS) sectors (27% each). Electricity consumption has been increasing in all of these sectors, most notably in the BTS sector. A very small fourth sector (at 4%) is transportation, in which electric energy has hitherto played a role solely with regard to railway transportation.

Electricity consumption by private households is caused by a variety of electric and electronic devices. In many respects, there is potential for energy saving: Replacing energy-inefficient devices, reducing standby losses and, amongst other things, replacing light bulbs in the area of electric lighting, this, however, being relatively unimportant. This cannot compensate, however, for the additional consumption of a continuously increasing number of devices and second sets – changes in consumer attitudes will have the greatest effect on energy saving. In the BTS and industrial sectors, the development of energy consumption is governed by economic growth for the most part; however, it is reduced by further and possibly substantial improvements in energy efficiency. Overall, electricity consumption, and thus the importance of electricity in the energy mix, is expected to continue to increase in the long run – estimates range around 1%-1.4% per annum.

Heating with small temperature differences –
Expediency of electrically powered heat pumps

When providing low-temperature heat for buildings (which accounts for 70% of the end-use energy consumption of private households), one has a large energy-saving potential which can be realised on the principle of “heating with small temperature differences”. Possible applications are combined heat and power (CHP) and heating using electrical heat pumps (see also chapter II.3 on CHP).

For the three basic functions of the “warm house” energy service – i.e. heating, ventilation and hot water generation – just one-third of the energy required for “conventional heating” would be sufficient. In order to keep the primary energy input as low as possible, an integrated concept is needed: Once thermal renovation of the building, including design of heating surfaces at low temperatures (floor heating or panel heating) and utilisation of “free” energy sources (solar power, waste heat, etc.) has been implemented, the remaining very low heating energy demand can be well met by electrical heat pumps.

Prospects and problems of electromobility –
Key element: batteries of high energy density

Electrically powered vehicles, or more generally, the electrification of traffic (catchword “electromobility”) can reduce the consumption of mineral oil and climate-impairing CO_2 as well as pollutant emission, provided the electric energy is not generated from fossil fuels. One great advantage of the battery-powered electric drive is its high efficiency (70-80% compared with 20-28% for combustion engines). However, this notion is put into perspective when, amongst other things, the efficiency of electricity generation, the energy invested in producing the battery and losses during load cycles are taken into account.

The central requirement is the development of suitable batteries: Even the most advanced lithium-ion batteries lag a factor of about five behind the target values in energy density and production costs, and despite great efforts in research and development there is no guarantee of success. It will thus take at least twenty more years, even under favourable conditions, before battery-powered electric cars are able to play a significant role in the market. The extent to when the vision of integrating electric cars into an “intelligent” grid and using their batteries as storage for fluctuating renewable energy sources can be realised, also remains to be seen.

Whether electromobility, be it battery-powered or fuel cell-powered, will play the role widely expected, has to be proven in competition with the “conventional” combustion engine (petrol or diesel), which is still expected to have considerable potential for development with regard to energy saving and CO_2 reduction (estimates assume 20-30% over the coming years).

2 Supply of electric energy – Various possibilities for a future energy mix

Fossil-based thermal power plants –
Necessity for CO_2 separation and storage

The use of coal (and increasingly of natural gas, combined about 63%) is predominant in thermal power plants worldwide and will continue to be so for many decades – at the same time, the burning of coal is the main cause of anthropogenic CO_2 emission. A further increase in the efficiency of power plants and/or the transition from coal to natural gas could reduce CO_2 emission from Germany’s fossil-based power plant fleet by possibly 15% and 25%, respectively, by the year 2030. However, the breakthrough necessary for meeting climate protection targets can only be achieved with the help of carbon capture and storage (CCS) technology.

Emission could thereby be lowered to 100 g CO_2/kWh, equivalent to a reduction of almost 90% as compared with 1990.

There are several promising procedures for separating CO_2. However, all of them still need to be developed to industrial maturity and tested in demonstration plants – their general implementation will therefore only be possible in some 10-15 years at the earliest, possibly even not prior to 2030. It is hoped that by that time renewable energy systems will be able to contribute a considerable share of the overall electricity supply. Otherwise, energy demand will still have to be met by the energy sources currently available.

While there will be technological solutions to the separation of carbon dioxide, its long-term storage is a much greater problem. Storage is envisaged in leak-proof geological formations: depleted mineral-oil or natural-gas fields, for which there is, however, only a limited storage volume available in Germany, and in so-called aquifers. Furthermore, the safety and effectiveness of this storage method remains to be proven and the consent of the affected general public still has to be won.

CCS technology has its price: The current state of the art reduces efficiency by 8-14 percentage points and thus increases fuel consumption, depending on the efficiency of the power plant, by typically 20-35%.

Nuclear power plants –
The only carbon-lean energy source so far apart from renewable energies

To some extent, there has been a reassessment of nuclear energy worldwide. International organisations (the IAEA, IEA, OECD/NEA, the EU and the IPCC) consider an increasing contribution of nuclear energy to the electricity supply to be necessary over the next few decades. The crucial factor in this assessment is, above all, climate compatibility, besides the issues of cost-effectiveness and security of supply. However, reservations about nuclear energy, primarily concerning disposal and operating safety, exist in various countries to varying degrees. Utilisation of nuclear energy is thus a political issue that is differently assessed by different nations.

Life cycle analyses of CO_2 emission from various power plant types show that nuclear energy is nearly carbon-free[1], similar to wind and hydro power. From a technical point of view, Germany's nuclear power plants are able to support the extension of fluctuating regenerative electricity generation via controlling power: they are designed for fast load changes in the upper power range (between 50 and 100% nominal power) and can also be operated in co-generation (CHP) mode.

Nuclear energy could significantly contribute to carbon-lean electricity supply in Germany, at least in the next two decades. It could also help to gain time for developing and introducing CCS technology. In particular, the loss of carbon-free electricity generation could be avoided through utilisation of nuclear energy in case the climate protection goals of the German government cannot be met within the fixed period of time despite speedy expansion of renewable energies. In that case, political deliberations about meeting climate protection goals, on the one hand, and the risks of nuclear energy, on the other, play a role beyond the factual aspects of this study.

---

[1] The remaining CO_2 emissions are due to the amount of fossil energy required for construction and fuel processing. They will be reduced in the long term when changing over to an energy system operating with less fossil fuel.

Utilisation of nuclear energy would thus have to be part of an integrated concept of energy and climate policies which would also have to determine the next and increasingly urgent course of action for disposal of highly radioactive waste.

Combined heat and power generation and system comparison –
Putting the advantages into perspective

Co-generation and utilisation of heat and electricity in combined heat and power (CHP) facilities is intended to improve fuel utilisation. It is regarded as an integral part of meeting the CO_2 reduction goals set by politics and the public (which is why the share of electricity from CHP is to be doubled to 25% by 2020). However, this study shows that many CHP facilities fall short of this expectation: A comprehensive comparison with separate electricity generation in a CCGT power plant and decentralised heat via a condensing boiler shows that the CHP facilities considered are only marginally better and, in some cases, even somewhat worse. Comparing a combination of a CCGT facility and decentralised electric heat pumps (with electricity from the CCGT facility) shows the CHP facilities examined to be even generally significantly inferior.

This example demonstrates that it would be a much more expedient energy policy to give incentives in general, e.g. by a “linear energy savings tariff” for energy savings which can actually be proven, rather than prescribe certain technological solutions.

As an integrated concept for the application of natural gas, it is proposed to cut down its ”mere combustion” in buildings and utilise it instead for electricity generation in centralised, highly efficient CCGT facilities. Having been thermally renovated, the buildings can then be heated by electric heat pumps supplied with electricity from these CCGT facilities.

Biomass power plants –
Increased utilisation of residual biomass, limited role for electricity

Biomass (and waste incineration) currently constitutes 3.1% of Germany’s electricity generation. This could probably be doubled in the next ten years. The overall biomass potential is expected to be >1.3 EJ/a and could theoretically contribute about a fifth of Germany’s gross electricity generation if it were used exclusively for electricity generation.

Worldwide, and also in Germany, energy crop cultivation is competing with food production in terms of land use – mainly because of the forced production of biodiesel (in Europe) and bioethanol (mainly in the US and Brazil). For this reason, development focuses on the cultivation of land not usable for other purposes as well as procedures for intensified utilisation of residual biomass (straw, waste wood, etc.) and unconventional biomass (e.g. algae). These second and third-generation processes still require intensified research and development. Taking into account that the replacement of fossil fuels for vehicles is regarded as the main utilisation of biomass, electricity generation from biomass will probably be at the lower end of predictions.

Solar electricity generation: photovoltaics –
Investment in public and industrial R&D is essential

Solar electricity generation (from photovoltaics and solar thermal heat) has great potential worldwide wherever favourable irradiation conditions prevail. In Germany, due to the low level of radiation, photovoltaics is virtually the only method usable for electricity generation, but the irradiation conditions put restrictions on these systems as well. On annual average, the power of German photovoltaics installations is thus only equivalent to a tenth of their nominal power and so their contribution to electricity generation is correspondingly small (2008: 0.7%). Weather-related fluctuations and the very small electricity yield in winter are unfavourable over here. Southern locations typically offer conditions superior by a factor of 2. Basically, photovoltaics in Germany, which does not generate electricity during the night and only small amounts in winter, cannot replace other power plants but only part of the fuel required for electricity generation by these, as long as adequate and sufficient means of electricity storage are not available.

Photovoltaics is the system which is the least competitive of all renewable energy systems. There are various approaches in research and development for both crystalline and amorphous Si-based systems, for thin film cells and also for the new organic and dye cells. However, the research intensity in the German photovoltaics industry (<1.5% of the business volume) is only about a tenth of what is invested in R&D by other research-intensive industries. Public R&D efforts, too, are rather modest when compared with the currently more than three-billion-euro annual market subsidisation currently provided under the EEG as well as with the increase in commitments by more than about 14 billion euros annually. Considerably enhanced R&D efforts are required in the public and particularly in the industrial area in order to enable German industry to gain a permanent strong international position.

Solar electricity generation: concentrated solar heat –
Promising source of electricity in the earth's sun belt requiring R&D

Electricity generation via concentrated solar heat (CSP) is only possible in (southern) regions having a high share of direct solar radiation, but there it has a large potential with well-balanced seasonal variation. Electricity generation can be extended into the evening or perhaps to full day and night operation by using heat storage units or fossil or biomass co-firing. High-voltage direct current (HVDC) transmission lines, the losses of which are comparatively low (<20% for 4,000 km), would need to be built for electricity transmission to Europe. Further research and development is important, in particular with regard to solar towers and storage technologies, and will decide whether the low electricity generation costs projected can be achieved.

Wind energy facilities –
Further development with offshore systems and wide-ranging crosslinking

Wind energy contributes by far the largest share to electricity generation from renewable energy sources in Germany: in 2009, 6.3% of the electricity generated was already provided by wind energy facilities (onshore); according to the extension scenarios of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety ("Leitszenario 2009"), this share could increase to up to about 15% by 2020 and up to about 26% by 2030 (about half of it offshore). Subsidisation of wind power as per the EEG currently already costs more than three billion euros per year (plus the commitments for the coming years resulting from the startup of every new wind energy system).

The biggest problem with wind energy (and to an even greater extent with photovoltaics) is the high fluctuations involved. Analysis shows that the power credit (which is that amount of conventional power that can be replaced with wind energy without reducing the security of the electricity supply) of wind energy systems installed in, and intended for, Germany amounted to nearly 10% in 2010 and will drop to about 3% by 2030 as a consequence of the increasing expansion in wind power. This means that initially 90% and later on 97% of the grid peak load needs to be backed up by other, so far mostly conventional, power plants in parallel to wind energy systems. In addition, a considerable controlling power (several gigawatts) is required in order to compensate for uncertainties in wind forecasting.

The demand for backup and controlling power would be significantly reduced if wind energy systems were crosslinked at as many different sites as possible. The creation of a European integrated electricity (super) network, therefore, is one of the most important prerequisites not only for the success of wind energy but, in general, for all efforts aimed at meeting long-term electricity demand via renewable energy sources.

Hydro power – Potential in Germany largely exhausted;
worldwide utilisation of marine energy still to be developed

Hydro power contributes about 16% worldwide and about 3.5% in Germany to electricity generation. It is almost exclusively generated by power plants located on rivers and reservoirs. In Germany the exploitation of the available potential is high and no significant further increase in capacity can be expected. Amongst the renewable energy sources, hydro power is an essential element for the supply of cost-effective and failsafe electric base load and controlling power.

Harnessing wave energy is still in its infancy. Wave power and surging billow systems yield about 10 kW per metre of lateral extension at wave heights of 1.5-2 m. There is almost no suitable location in German waters for the large-scale utilisation of wave energy as well as of ocean currents or the falling and rising tides. Osmosis power plants, which utilise the salinity gradient of sea water and freshwater at estuaries, have only limited practical potential here as well. Marine energy could contribute a notable share of electricity generation worldwide, but practical problems have so far hampered significant extension of it and further research and development is required.

Electricity from geothermal sources – Almost untapped;
capable of base load and interesting to many regions in the world

Geothermal energy has been utilised for electricity generation since the beginning of the 20th century and currently provides an electric power of >10 GW_e worldwide; a growth in the double-digit percentage is expected. An exploitable potential of 50 GW_e is assumed for Europe; regions featuring geothermal anomalies are particularly attractive. In Germany (potential of about 10-15 GW_e for about 100 years), one needs to drill to a depth of at least 3,000 m, often to >5,000 m, in order to achieve a sufficient temperature difference.

In Germany, but also in many other regions of the world, utilisation of geothermal electricity generation is still mostly in the testing stage, and learning curves with considerable cost reductions can be expected for the technologies required. As a matter of principle, geothermal energy allows electricity generation with high availability and low emissions without unfavourable seasonal and daily variations. German technology could gain a considerable share of the rapidly growing international market if adequately supported by research and development.

Fusion power plants –
Long-term R&D with high hopes for the future

Fusion power plants can provide base load electricity because their operation is generally not subject to daily or seasonal or weather-related fluctuations. The feedstock fuels, deuterium and lithium, are non-radioactive and the operation of fusion power plants ought to have a very good environmental balance. In principle, there are no major risks comparable to those with nuclear fission. Also, the materials being developed should make it possible to avoid the necessity of final disposal of large amounts of long-lived radioactive material. In this way nuclear fusion could largely contribute to clean, safe and guaranteed electricity supply in the long term.

However, a significant amount of R&D is still needed in this technology, which is being advanced by the concept of magnetic confinement, as part of the international ITER project in particular. Since highly efficient laser drivers have become available, the possibility of generating energy by means of laser-induced inertial confinement fusion has recently become the focus of more extensive studies in the EU, the US and Japan. With successful development, nuclear fusion could become an important source of electricity generation in the second half of this century.

3 Distribution of electric energy

Grids and systems considerations – Crucial for supraregional synergy, supply security and efficiency

The massive expansion of fluctuating renewable electricity generation poses new qualitative challenges to the grid. The situation will considerably deteriorate if the share of wind energy further increases and if during strong wind periods more power is generated than consumed in areas of major distribution; this would require a corresponding extension of the grid capacity unless large, temporally flexible options for consumption, e.g. via hydrogen production (for feed-in purposes into the natural gas grid) or other storage options are developed. In any case, a grid featuring a large, wide-ranging (also Europe-wide) transmission capacity and intelligent network management is required for supra-regional balancing of fluctuating electricity generation and for efficient electricity trade. The local distribution grid, too, should be made intelligent via communication technology in order to facilitate a new quality of tariff flexibility and consumption management. It remains to be seen whether this smart grid will help reduce electricity consumption, which is essential in the overall context.

Electricity storage – Of great importance, but of limited potential so far

Only pumped storage power plants are currently available for cost-effective electricity storage on a scale relevant to the load management in the entire electricity network; however, their potential cannot be greatly extended in Germany, and in Europe, only Norway still has a large untapped potential, which, however, is limited by environmental regulations. Adiabatic compressed-air energy storage units (including integrated heat storage) could become relevant for large-scale application but they have not yet been tested and their system costs will probably be considerably higher. Electrochemical storage units have generally not yet been considered for large-scale network management, due to their low storage capabilities and their high cost. In the context of electricity storage, the development of heat storage units for solar thermal power plants needs to be mentioned (they take over the role of electricity storage units here). These allow electricity generation to be extended into the evening or even to full 24-hour operation.

The coming year should see further improvements in vehicle batteries and fuel cells as a result of ongoing, intense, worldwide research efforts. Should electric vehicles eventually represent a significant share of the overall vehicle fleet, their batteries could be used for storing electricity – it remains to be seen whether this will develop into an essential element of a smart grid.

4 Outlook – Electricity as the key to a sustainable and climate-compatible energy system

This study mainly examines issues regarding electricity utilisation and supply in the near and medium-term future (time period up until 2030). However, the long-term prospects towards a system of electric energy supply whose CO_2 emission is continuously being reduced are addressed as well. This prospect is not unrealistic: 50% of German electricity could be generated carbon-free by about 2020 if the goals of renewable energies are met and the current contribution of nuclear energy is not replaced with CO_2-emitting forms of energy. If 75% of electricity generation is carbon-free at a later date, the generation of a kilowatt-hour will release less than 200 g CO_2 on average – instead of the present 572 g CO_2 in Germany. Thus, from the point of view of climate protection, electricity would become more attractive than natural gas, even for conventional space heating (at the same time, of course, the criterion of cost-effectiveness needs to be met) – with heat pumps it would be attractive even much sooner. In the transportation sector, the development of suitable batteries or fuel cells will largely govern the extent to which carbon-lean electricity or hydrogen produced from electricity will then replace fossil fuels.

For mitigating the climate change it is only the global restructuring of the energy system that counts, and here German industry ought to play an essential role. The crucial elements for success will be research and development.

* * *

Introduction

It is a fact proven by many analyses that global warming with its huge dangers to nature and society is driven by the increase of the atmospheric CO_2 concentration. However, scientific studies (see, for example, [1, 2]) also point out that mankind should still be able to mitigate climate change and its consequences, provided that the temperature increase can be limited to two degrees. In order to stay within this limit, anthropogenic CO_2 emission must be drastically reduced. To achieve this it is of utmost importance to revise our present system of energy supply and utilisation, which, due to its massive use of fossil fuels, is the main cause of anthropogenic CO_2 emission. The other major contributor to atmospheric CO_2 is the biosphere, which, however, can hardly be influenced. A most economical use of energy and the transition towards carbon-lean or carbon-free energy technologies therefore need to be vigorously pursued.

Already in 2005, in respect of the German situation, the German Physical Society (DPG) examined these issues in its study "*Klimaschutz und Energieversorgung in Deutschland 1900-2020* / *Climate Protection and Energy Supply in Germany 1990-2020*" [3]. The present study complements its predecessor by providing a survey and forecast of the role which electricity could play in terms of energy supply in a society intent on reducing CO_2 emission. First and foremost, this study is being carried out for Germany with a time horizon of about 2030; however, where appropriate and possible, a wider temporal and spatial perspective is considered.

The predominant areas of energy application are heating, fuels and electricity. There is an obvious reason for focusing this study on electricity. Its consumption has been steadily increasing over the past decades because it affords particular advantages. Electricity can easily be generated by means of various technologies, it can be readily transported and its use is extremely comfortable and flexible – a vast number of electric devices and technologies have become indispensable to our private everyday lives, to economy and to society, and there is much evidence that the significance of electricity in the interplay of the various forms of energy will continue to increase.

Before turning to the supply of energy, one should first address the saving of energy, since reducing consumption and losses results directly in reduced power plant capacity requirements and minimisation of CO_2 emission and simultaneously in saving fuel and construction material resources. Of huge importance is also the reduction of losses during conversion from one form of energy to another, particularly from fossil energy to electricity. Here, first of all, efficiency enhancements in fossil-based (and nuclear) thermal power plants need to be addressed. It will depend on the power plant mix whether for some areas of application, in relation to the primary energy input required, direct use of fossil fuels will remain more favourable than utilisation of electricity: With an increasing share of renewable energy systems which employ non-thermal conversion processes (e.g. wind) or which are not limited by finite resources (e.g. solar heat), conversion losses during electricity generation will become less important. As a consequence, reduction of end-use energy consumption will then come into focus, i.e. optimisation of end-use energy generation from electricity and the avoidance of unnecessary end-use energy consumption.

Discussion of restructuring the energy supply system cannot remain restricted to Germany. In economy and energy politics European and international interdependence is much too strong as to allow a successful solo attempt. Only worldwide reduction of CO_2 emission and conservation of resources makes sense anyway – with regard to climate, sustainability and also avoidance of economic imbalances. The world market for advanced energy technologies, already impressive, will continue to grow enormously due to political bids for agreements on climate protection. For this reason – and in view of the importance of exports to Germany's economic performance – not only are research and development efforts necessary with regard to the national energy supply, they also need to be oriented towards the global market to at least the same extent.

Also, some technologies having only a minor technological or economic potential in Germany, e.g. solar, marine or geothermal energy, could gain great importance in regions of the world with more favourable conditions. Correspondingly, it also has to be asked whether the German programmes for market subsidisation of regenerative energy systems are at their optimum in view of an integrated European energy market, international competitiveness of the German economy and the Europe-wide or global development towards carbon-lean energy generation.

Discussion of the latter issue also touches upon questions such as time periods for economic amortisation of investments in fossil or renewable energy systems or nuclear power plants. Amortisation usually takes decades; for that reason, decisions made today have a significant effect on the long-term future: fossil-fuelled power plants currently planned in Germany, and above all worldwide, will be in operation for decades. Consequently, the requirements for balancing and reserve power for fluctuating renewable energy systems (but also the utilisation of fossil fuels in decentralised combined heat and power facilities) impose long-term dependence on fossil energy, which is actually unwanted and makes optimisation of fossil-fuelled power plants and development of technologies for carbon capture and storage (CCS) an important matter in this study.

Electric energy requires a transmission network including system control which can balance generation and consumption at any time, since storage of electricity so far has severe limits compared to the situation with fossil fuels. Power plants and consumers are thus integrated in a coupled system which has to be regarded as one entity. Here the enormously increasing share of fluctuating feed-in from wind energy facilities imposes considerable, novel requirements on network and balancing power. If the usual supply reliability is to remain guaranteed in Germany, the nominal capacities of these power plants need to be essentially adjusted to weak wind conditions, a high reserve capacity of other suitable systems for electricity generation is needed as backup and further electricity storage has to be built, if possible. Furthermore, the supraregional and European transmission network needs to be extended, since only an efficient and intelligent grid with wide-ranging and large capacities for electricity transmission can effectively contribute to minimising the issue of fluctuating electricity generation, furthering the electricity trade and saving costs and energy by creating possibilities for matching power consumption and electricity generation. The necessity of extending such a grid in the European context has been obvious for a long time. With regard to the still unsolved issue of electricity storage all possible large-scale storage methods will be discussed in this study (including the utilisation of surplus amounts of electricity for hydrogen production). Perhaps also the future Li-ion or metal-air batteries of electric cars can contribute to storing electricity – this calls for intelligent load management of the regional and local grids, as pursued with the idea of a ‘smart grid’.

Will increased utilisation of electric energy have a positive effect on the climate? Today, the main energy carriers, apart from electricity, are coal as well as liquid and gaseous hydrocarbons. Electricity has clear advantages over them: It does not cause emission at the user’s site and can be generated virtually carbon-free with renewable energy systems as well as nuclear power (and possibly nuclear fusion in the long term)[1] and, carbon-lean, in fossil-fuelled CCS power plants. With regard to Europe and Germany, security of supply could thus improve at the same time, since several of these carbon-free energy systems are much less dependent on limited or regionally unevenly distributed resources than is the case with natural gas and oil. Increasingly carbon-free electricity generation will also make space heating with electric heat pumps more attractive than fossil-fuelled condensing boilers or combined heat and power facilities, from the point of view of climate protection and perhaps also economics. The significant use of fossil energy for space heating could thereby also be replaced by carbon-free (or carbon-lean) electricity.

[1] None of these energy systems releases CO_2 during operation. Their electricity generation causes CO_2 emission only because fossil energy is partly used for the construction of these facilities. This share, however, will decrease with the renewal of our energy supply system and could eventually become insignificant.

In the long term, electricity could thus become the key to guaranteed, sustainable and climate-compatible energy supply and to efficient, flexible and comfortable utilisation. It is not known, however, which methods of electricity generation will predominate – given the current state of knowledge none of the known possibilities will be able alone to meet the multitude of requirements, such as cost-effectiveness, social acceptability, environmental and climate compatibility and other criteria. It is obvious that fossil-based energy will long continue to play a significant role, but it is also apparent that development towards the different non-fossil energy technologies will be pursued, thereby laying foundations for increasing significance of electricity in the Germany's, Europe's and the world's energy supply. Along this road, broad-based and persistent R&D work is the fundamental requirement for success.

Notes and references

[1] Nicholas Stern, *The Global Deal – Climate Change and the Creation of a New Era of Progress and Prosperity*, PublicAffairs, New York, 2009

[2] Wissenschaftlicher Beirat Globale Umweltveränderung, WBGU (German Advisory Council on Global Change), *Kassensturz für den Weltklimavertrag – Der Budgetansatz* (German only; translation: *Cash Check for the Global Climate Contract – The Budget Estimate*), special report, July 2009

[3] Study by the Deutsche Physikalische Gesellschaft, DPG (German Physical Society), *Klimaschutz und Energieversorgung in Deutschland 1990-2020 / Climate Protection and Energy Supply in Germany 1990-2020*, September 2005

Part I: Use of electric energy

I.1 Utilisation sectors (private households, business, industry)

More than one third (35.5%) of the primary energy used in Germany (1990: 14,905 PJ, 2009: 13,281 PJ[1]) is lost through processing and conversion[2]. The major part of these losses is due to the generation of electricity by thermal power plants (from fossil, nuclear or renewable fuels). There is an enormous potential for energy saving in this regard which will be discussed in a later chapter. This chapter, however, does not focus on primary energy but on “final energy” already processed for the consumer. The first observation made is that, again, nearly one half of this final energy consumption (2007: 8,581 PW) is lost (particularly as unwanted heat) during application (vehicle engines, industrial plants, machines, electric lighting, etc.), and only the rest (2005: 52% or 4,864 PJ) is converted into the required effective energy for the desired energy services. On an absolute scale, this loss is nearly as large as the one occurring during the conversion of primary into final energy. Utilising the potential for loss reduction through a significantly improved energy efficiency of devices and processes is therefore of equal importance when using final energy.

Final energy consumption, just as with the primary one, has increased considerably in Germany in the decades following World War II. Stagnation can be observed only since 1990, and consumption has even dropped slightly in recent years (see Fig. 1) – the decrease from 9455 PJ in 2004 to 9149 PJ in 2006 appears to be continuing (to 8581 PJ in 2007, although 9126 PJ were consumed in 2008). Overall, final energy consumption in Germany is down by 3.5% as compared to 1990, despite a considerably higher economic output[3]. Thus, the final energy consumption intensity of the overall economy[4] has decreased by more than 25% since 1990.

Sectors	Final energy consumption (2007)	Thereof: electricity consumption (and percentage of the total electricity consumption)
Industry	2441 PJ (28.45%)	816 PJ (42.8%)
Business, trade, services	1342 PJ (15.64%)	522 PJ (27.4%)
Private households	2201 PJ (25.65%)	508 PJ (26.7%)
Transportation	2596 PJ (30.27%)	59 PJ (3.1%)
Total	**8581 PJ (100%)**	**1904 PJ (100%)**

Tab. 1: Final energy and final energy consumption by sectors[5] – Germany 2007

---

[1] 1 PJ = 1 million t SKE/29.3 = 34.121 t SKE.

[2] Figures on this and the following pages are given for Germany as per AGEB (Arbeitsgemeinschaft Energiebilanzen; Working Group on Energy Balances) and BDEW (Bundesverband der Energie- und Wasserwirtschaft; German Association of Energy and Water Industries) (2008 and 2009: preliminary figures). For 2008, primary energy consumption was an estimated 14280 PJ (source: AGEB_Energieflussbild_2008_kurz20090925; German only; translation: energy flow diagram by the Working Group on Energy Balances). The terms primary, final, and effective energy are used in the same sense as in the documents issued by the AGEB.

[3] Source: AGEB (Arbeitsgemeinschaft Energiebilanzen; Working Group on Energy Balances), 2008. In 2007, consumption decreased more notably than in previous years despite an economic growth of 2.5%. The main reason for this is private consumption. Average temperatures were above the long-time average during the heating period (source: DWD [Deutscher Wetterdienst; German Meteorological Service] citing T. Fleiter et al., BWK [Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau; Association of Engineers for Water Management, Waste Management and Land Improvement], Vol. 60 (2008) No. 4, p. 140). However, notably increased electricity costs may have had an impact. AGEB, 2008.

[4] Primary energy intensity has decreased by about the same amount. (Source: AGEB [Arbeitsgemeinschaft Energiebilanzen; Working Group on Energy Balances], citing T. Fleiter et al., BWK [Bund der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau; Association of Engineers for Water Management, Waste Management and Land Improvement], Vol. 60 (2008) No. 4, p. 139)

[5] Source: BDEW (Bundesverband der Energie- und Wasserwirtschaft; German Association of Energy and Water Industries), Energie-Info (German only; translation: Energy Information), Dec. 2008

For the purpose of statistical investigation, final energy consumption is divided into four utilisation sectors (see Tab. 1). The sectors *transportation*, *industry* and *private households* are the largest ones and show, depending on the year, more or less the same consumption values. In contrast, consumption in the *business, trade, services (BTS)* sector[6] is 40% less.

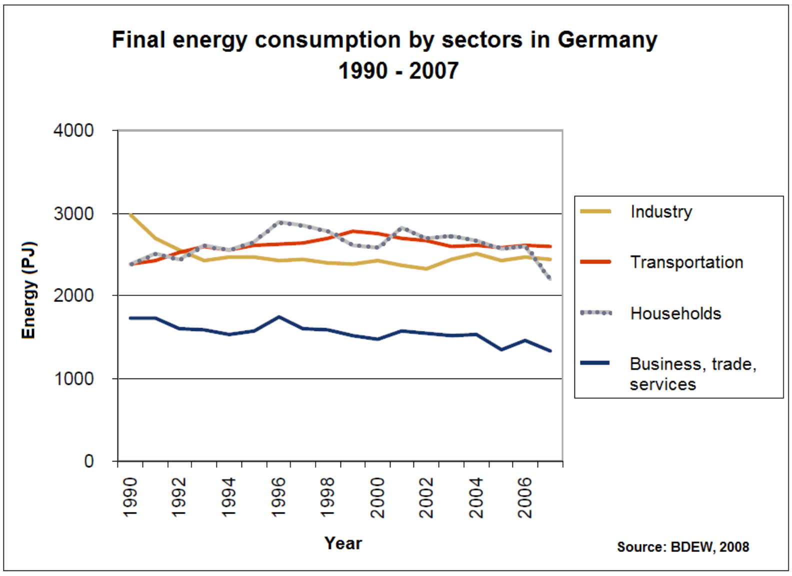


Fig. 1: Final energy consumption in Germany by sectors (1990-2007)

In attempting to reach the long-term target of a climate-compatible energy supply, the European Commission has formulated sector-specific energy saving targets for the year 2020 in its Green Paper on Energy Efficiency[7] with the intention of increasing energy efficiency by 20% in total. In order to implement these measures a multitude of actions have been taken and more are under way[8]. They include tightened requirements for energy-efficient products, buildings and services; an improvement of energy conversion[9]; and particularly for lowering energy consumption in the transportation sector. Overall, the further increase of energy efficiency is one of the most important factors with regard to the targets of the Kyoto Protocol and the ongoing efforts to limit the effects of climate change. In addition to technical and regulatory requirements for devices and processes, economic and political incentives and framework conditions are intended to effect a change of attitude with regard to energy use - all of this, if possible, as part of an international agreement to avoid market distortions.

Between 1990 and 2006, the percentage of electricity of final energy consumption in Germany increased from 17.5% to 19.6%, while 22.2% are estimated for 2007. Hence, electric energy, which is used in various ways in the industrial and BTS sectors and private households, plays an ever more important role. Not only has its percentage but also the absolute amount of electric energy[10] been increasing steadily and this development is likely to continue in the future. On an international scale, the very same trend towards an

[6] The BTS sector also includes other consumers, amongst them the military and street lighting (source: BDEW [Bundesverband der Energie- und Wasserwirtschaft; German Association of Energy and Water Industries] and Stadtwerke Chemnitz [Chemnitz municipal utility])

[7] European Commission Green Paper on Energy Efficiency [COM(2005)265]. Action Plan for Energy Efficiency [COM(2006)545{ SEC(2006)1173-1175}] with its “20/20/20” target (20% more renewable energy, 20% less CO_2 emissions, 20% more energy efficiency by 2020)

[8] See, e.g. Directive 2005/32/EC, later known as the Energy Star Programme

[9] In particular with regard to combined heat and power as well as local energy supply

[10] 1990: 1638 PJ, 2007: 1904 PJ (preliminary figure). Source: AGEB (Arbeitsgemeinschaft Energiebilanzen; Working Group on Energy Balances) 2008

increasing use of electric energy can be observed, and electricity may be considered the most attractive type of energy in most areas of application by industrial, commercial and private consumers.

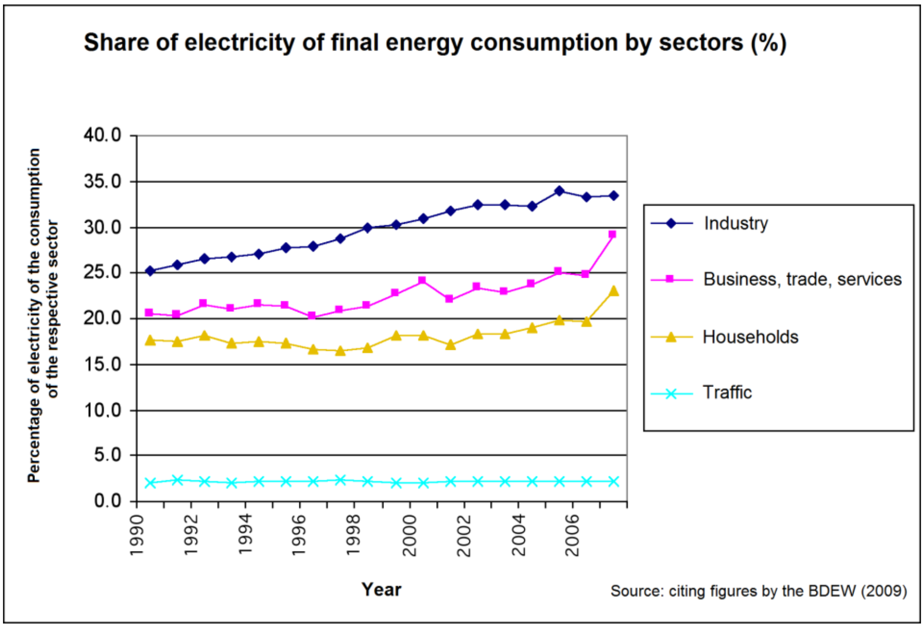


Fig. 2: Percentage of electricity of final energy consumption by sectors (Germany)

All sectors have a part in the increase of electricity in the mix of final energy consumption both in Germany and internationally (see Fig. 2) aside from the transportation sector, which is discussed only in passing in this study since electricity plays only a minor part in it with little change[11]. The absolute growth is highest in the BTS sector, reflecting, on the one hand, the transformation into a service society that allows this sector to grow, and on the other, a considerable rise in quality standards that is reflected, for example, in the number of buildings being fully air-conditioned year-round[12] or of workplaces being equipped with electronic devices.

Sectors	Share of electricity consumption in Germany 1994-2004[13] / 2007[14] (in parentheses EU-27, 2004[15])		Increase of the share of electricity consumption p.a. (Germany) during 1994-2007[15]	Share of electricity of final energy consumption of the respective sector (Germany, 2007)
Private households	29% / 26.7%	(28.8%)	+0.85%	23%
Business, trade, services	23% / 27.4%	(25.3%)	+3.1%	39%
Industry	45% / 42.8%	(41.6%)	+1.4%	33%
Transportation	3% / 3.1%	(2.7%)	+0.2%	2.3%
Total	**100% / 100%**		**+1.6%**	**22.2%**

Tab. 2: Use of electricity and increase of the electricity percentage by utilisation sectors (1994-2007)

[11] It is due almost exclusively to railway transportation. For electromobility see Ch. I.3.

[12] This effect is not reflected fully by the data of the BTS sector as the energy required for heating and air-conditioning buildings with mixed utilisation (businesses plus private households) is attributed regularly to private households. (Source: BDEW [Bundesverband der Energie- und Wasserwirtschaft; German Association of Energy and Water Industries])

[13] Data according to VDE (Verband der Elektrotechnik, Elektronik und Informationstechnology; Association for Electrical, Electronic & Information Technology) Effizienzstudie (German only; translation: Efficiency Study) 2009

[14] Data according to BDEW (Bundesverband der Energie- und Wasserwirtschaft; German Association of Energy and Water Industries), Energieinfo (German only; translation: Energy Information) 12/2008

[15] JRC (Joint Research Centre, European Commission), EUR 22753 EN, 2007. At the EU level, 2% of the electricity consumption in agriculture is listed separately.

With the increasing consumption of electric energy, CO_2 emissions need to be reduced, i.e. electricity must be produced more efficiently and without the use of fossil fuels in order to save fossil primary energy.

1.1 Private households

Of the final energy consumption in private households (25.6% of the total final energy) almost 88.6% was used for heating purposes in 2007[16]. About 5% is used for cooling and freezing, less than 2% each for light and communication, the rest for various applications. Therefore, the main focus must clearly be on energy saving with regard to heating[17] and hot water. Building services engineering measures (insulation, ventilation, heating and hot water systems) in particular are crucial. Replacing the two million remaining direct and electric night storage heaters and the large number of older heating systems with modern natural gas or oil condensing boilers is also important. In view of the slow replacement cycles of the 36 million homes in Germany it must be kept in mind, however, that the changeover to modern natural gas or oil-fired heating or combined heat and power systems cements the nationwide long-term use of fossil fuels.

Ground-coupled and air heat pumps, which are also able to provide cooling during summer, offer an alternative to a thermally well-insulated living space. Their application would increase electricity use for space and water heating but reduce or even nearly avoid CO_2 emissions altogether if electricity is generated from non-fossil sources, i.e. mostly CO_2-free types of energy such as renewable energy systems or nuclear energy and, perhaps in the future, fossil power plants using CCS technology.

In the medium term, a considerable increase can be expected in the use of heat pumps[18]. At present, however, this attractive form of heating is not yet very common. As a rule of thumb, the changeover of one percent of homes to heat pump systems increases power consumption of private households by 1% if, at the same time, these homes are insulated according to a heat demand of 60kWh/m^2. A long-term goal of space heating using heat pumps would only, under that premise, result in a doubling of the electricity demand.

Electricity use in private households has been increasing continuously. The reasons are, amongst other things, a higher number of electric appliances per household[19], particularly dishwashers, dryers, freezers, air

---

[16] Of those 88.6%, space heating accounts for 71.28%, water heating for 12.04% and further process heat (cooking, hot water for washing, etc.) for 5.31%. Source: BDEW-Info, December 2008. Figures for East Germany are even higher in parts (source: Stadtwerke Chemnitz [Chemnitz municipal utility).

[17] German heat energy demand amounts to about 426 TWh/a. Today, oil, gas, and solid fuel heating systems are highly efficient in general, in particular condensing boilers. No significant further energy savings are to be expected from this technology (that is, if heat pumps are not used). In contrast, it is expected that a low two-digit percentage of energy can be saved as a result of improving heating and heat demand control.

The biggest savings can be achieved by optimising the building skin and ventilation system. The yearly energy demand for buildings older than 50 years is about 300 kWh/m2 while today's buildings require about 150 kWh/m2, even though tried and tested solutions for the mass market are available for low energy houses, e.g. according to KfW-60 and KfW-40 standards of 60 – 40 kWh/(m2a) (or better). Even better figures can be reached in practice as passive houses demonstrate.

If the heat demand of a KfW-60 construction design were reached on average, the heat energy demand would be only about 120 TWh/a. The large number of old buildings, however, poses complex practical requirements; for these, concepts for broad application need to be developed (further). Very thin vacuum insulation elements open up new possibilities in this regard. Overall, within two decades the energy demand for space heating may be reduced to one third of today's demand.

The low heat demand remaining for low energy houses might make the installation of natural gas or oil heating systems (particularly using heat pumps) overall uneconomic when compared with electricity. See the corresponding chapter of this study.

[18] The German Federal Government estimates the electricity demand for electric heat pumps to be 3 TWh/a (2020) and 7 TWh/a (2050), corresponding to 3% and 5% respectively of today's electricity demand of private households. ISES/BEI (Institut für ZukunftsEnergie Systeme, Saarbrücken; Institute for Future Energy Systems / Bremer Energieinstitut) estimates the present electricity consumption of heat pumps to be <1% of today's electricity consumption for heating purposes, that is <0.17 TWh.

[19] Refrigerators and freezers are the largest consumers of electricity at 30% and 17% respectively (together nearly 50%) among large household appliances (washing machines 18%, dryers 8%, dish-washers 10%, TV sets etc. 18%).

conditioning and electronic devices (PCs, TVs, home entertainment systems, cordless telephones, broadband connections[20] etc.) – many of which are second or third devices, particularly TVs[21], refrigerators and freezers – as well as their increasing operating time. In addition, the number of households is increasing, in spite of a constant population, due to declining family size and increasing comfort demands because of, amongst other things, the higher average age of the population[22].

On the other hand there are many ways of saving energy. Amongst these are:

- Replacing older household appliances consuming a high amount of electricity. These include refrigerators and freezers, dish washers, washing machines, dryers and analogue TV sets in particular[23].
- Reducing standby power consumption of electronic devices by improving the circuitry or suitable external measures. This applies to TV sets[24], coffee machines, computers, printers and multifunctional devices, external power supply units/charging devices in general[25], telephones, home entertainment devices, transformers for halogen lamps and more.
- Replacing light bulbs[26]: Household lighting accounts for <1.8% of the final energy consumption (or 8.1% of the electricity consumption of private households, or <2.2% of the total electricity consumption in Germany[27]). It has received great political attention even though the saving potential is rather limited[28] and modern so-called energy saving lamps leave much to be desired[29] with regard to quality of light, turn-on characteristics[30] and lifetime when considering a high number of make-and-brake

[20] Germany had 20 broadband connections per 100 phone lines in 2006. That is a low number in comparison with other countries (for comparison: Belgium 26, France 30, Finland 38). Source: JRC (Joint Research Centre, European Commission)

[21] Germans own about 47 million TV sets. The tendency in Europe is towards leaving the TV switched on longer (1995: 205 minutes/day, 2005 232 minutes/day; source) (Source: GfK [Growth from Knowledge] citing JRC [Joint Research Centre, European Commission]).

[22] The distribution of electricity use in Germany and the EU is quite similar as Tab. 2 “electricity use and increase of the electricity percentage by utilisation sectors” shows. Therefore, statistical data of both regions can be used (in particular data of EU-15, i.e. without the newer member states, are useful).

[23] The first generation of 21-inch colour TV sets needed 500W to run. Today‘s sets require 50 W.

[24] The average standby loss of TV sets has decreased from 6.2W (1995) to 2.2W (2005). The industry’s Energy Efficiency Index (EE-Index) includes the industry’s self-commitment to a maximum standby loss of about 1W from 2007 on. (Source: EICTA, TV-Self-Commitment Report July 2005, http://www.eicta.org/web/news/telecharger.php?iddoc=381)

[25] The degree of efficiency of external power supply units (e.g. laptops, printers, halogen lamps) ranges between 50% and 85%. No-load losses have already decreased significantly during the last decade.

[26] In 2007, 90% of all lamps sold were still conventional light bulbs. (Source: Hans-Joachim Kamp, Philips, interview in German newspaper “Hamburger Abendblatt” 4 February 2008.) The European Commission estimates that about 8,000 jobs are still tied to the production of conventional light bulbs in Europe.

[27] The BTS sector consumes almost three times as much electricity. However, light bulbs play virtually no role in this regard. Overall, the amount of energy used for lighting increased by about 15% between 1990 and 2002 (source: Enerdata/Odysseus/Mura)

[28] Germany has a comparatively low percentage. In other countries (particularly, but not exclusively, the Scandinavian ones), lighting accounts for between 9% and 20% of the final energy consumption in the household sector. (Source: JRC)

[29] As the rapidly increasing market share of energy saving lamps demonstrates, this type of lamp has been accepted by the population for various lighting purposes. If their use were advantageous in all respects, a regulation that removes regular light bulbs from the market would not be necessary.

[30] Energy saving lamps are slow: initially, they have only about 50% of their final brightness and need up to three minutes, depending on temperature, to reach full brilliance. Expensive pre-heating lamps need up to two seconds before they shine at all (source: Kraus Technology Consultant). This drawback is supposed to be less significant in the new electrode-free energy saving lamps.

cycles (e.g. corridor lighting), health and environmental aspects[31]. Semiconductor diode-based lighting[32] is slowly approaching market penetration.

- Electrical resistance heating: About two million electrical heating systems (direct resistance or night storage heaters) are used in Germany. Electricity consumption increased by 5.7% in the decade from 1995 to 2004 and is estimated to represent 13% of the total electricity demand of private households[33,34]. Built-in electric space heating accounts for 21% of the electric consumption of private households in the EU and for 29% if fireplace inserts and mobile electric heaters, popular in the U.K., are included. These heaters operate at a very low level of efficiency in relation to the primary energy content of the fossil fuel used for electricity generation[35].
- Electric water heating: Consumption decreased by about 5% between 1995 and 2004. There still is, however, a considerable potential for saving energy.
- Avoiding or reducing electricity consumption by altering consumer habits. Considerable savings might be accomplished in the household sector that way; however, it would require interfering with the population's habits and need for convenience. If energy prices keep continuing to account for a drastically and ever more increasing share of living expenses, as they have done in recent years, the population will (have to) adapt. Private household consumption in 2007 seems to support this tendency.

The smart grid[36] is a new concept intended to optimise the interaction between energy market participants and, in particular, power plant capacity and grid load. It is intended to inform the end consumer of the current costs of electricity and adjusts – automatically in the long-run – the tariff to the load or the electricity consumption of devices to electricity supply. To what extent substantial savings in the use of electric energy can be achieved this way remains to be seen.

Overall, a considerable decrease in final energy consumption in the private households sector due to improved building services engineering can be expected; however, electricity consumption is expected to increase more rapidly than in the past. It is expected that the tendency to replace fossil fuels for the purpose of space heating with electric energy and ambient heat with heat pumps will grow significantly in the long run and that the increasing number of electric appliances and information, communication and home entertainment equipment will overcompensate for a possible increase in efficiency and avoidance of standby losses.

---

[31] Energy saving lamps contain mercury. Assuming 10 lamps per household and an average lifetime of two years for compact energy saving lamps about 180 million lamps are needed in Germany each year. They contain one quarter of a ton of the environmental toxin mercury. Large rates of save recycling are therefore indispensable.

[32] In the future, organic LEDs may also be able to play an important role as surface radiators; at present, however, they are far from being competitive large-scale applications.

[33] Source: ISES/Bremer Energieinstitut (Institut für ZukunftsEnergie Systeme, Saarbrücken; Institute for Future Energy Systems / Bremer Energieinstitut), *Energieeffizienzpotentiale durch Ersatz von elektrischem Strom im Raumwärmebereich* (German only; translation: *Potential for Energy Efficiency by Replacing Electricity in Buildings for Space Heating* (http://www.bmu.de/files/pdfs/allgemein/application/pdf/studie_stromheizungen.pdf). The general energy demand for space heating increased by only 2.8% during the same period.

[34] Source: BUND (BUND für Umwelt und Naturschutz, Deutschland – Freunde der Erde; Friends oft he Earth) citing Verivox (consumer portal for energy and telecommunications). ISES/BEI (Institut für ZukunftsEnergie Systeme, Saarbrücken; Institute for Future Energy Systems / Bremer Energieinstitut) estimate 1.44 million homes (i.e. every twenty-fifth home) and a share of 4.1% of the final energy consumption.

[35] See, for example, the corresponding discussion presented in the study of electrical heating by ISES/BEI (Institut für ZukunftsEnergie Systeme, Saarbrücken; Institute for Future Energy Systems / Bremer Energieinstitut), loc. cit. The considerations of that study refer to its present use. Electric heating can be useful and attractive when used in low-energy houses with heat pumps for which electricity is being generated from renewable sources. Also see footnote 17.

[36] See, for example, http://www.smartgrids.eu/, or http://www.bundesnetzagentur.de/enid/2/2__7/Intelligentes_Stromnetz_3ub.html

1.2 Business, trade, services

This sector reflects the transition to a service society. Electric energy plays an important and increasing role in it – the absolute use of electricity has increased by 37%, or, in other words, the share of electric energy in the final energy consumption of this sector went up from 24% (1990) to 38.9% (2007). Part of the reason is that workplace requirements have developed considerably over the past decades. The number of fully air-conditioned office buildings, for example, keeps continuing to increase significantly and the employee's information technology equipment has evolved from monitors connected to a central server to workstation computers with additional devices such as printers and scanners[37].

Lighting is the largest consumer of electricity in this sector with a share of 26%-30%[38]. A significant energy saving potential is not expected as fluorescent tubes dominate clearly; their modern variants distinctly outperform all energy saving lamps relevant to the private households sector with regard to light yield per watt.

The rapid increase of electricity consumption in this sector by more than 3% per year during the last decade may be slowing slightly. There are no signs for a reversal of the trend[39], however, and it is unlikely to take place without regulatory requirements.

1.3 Industry

The industrial sector (which in Germany includes the mining industry that is being phased out) has always tried to save energy to the extent that these efforts impact favourably on the cost-effectiveness analysis. Due to the increasing energy prices over the past decades – and particularly in recent years – energy saving measures have been intensified considerably.

An overview of the use of electric energy in the industrial sector is much more complex than that in the private households or BTS sectors, since a large number of different facilities and devices contribute to consumption – from robots and conveyor belts, used e.g. by the automobile industry, via electric steel ovens, to beverage bottling plants, from welding apparatuses or vacuum testing facilities to CNC machines, to name only a few.

At the component level variety decreases – at least with regard to the use of electric energy. The most important groups are engines (small drives, three-phase motors and large drives), transmission gears, inverters, power supply equipment and lastly lighting. The latter includes powerful high pressure discharge lamps which play no role in the households sector and only a limited one in the BTS sector but whose light yield outperforms all other lamps with regard to energy efficiency.

Studies such as the one by the VDE[40] indicate that, with the expected long-term increase in economic performance, industrial energy consumption may increase by about 30% between 2007 and 2025 – even

---

[37] To what extent the currently increasing tendency to store applications and data online might be able to halt this trend in the future remains to be seen.

[38] Consumption in the EU-25 is estimated to be 175 TWh/a (JRC [Joint Research Centre, European Commission], 2005) and 197.6 TWh/a (projection for 2010). European statistics refer to the BTS sector as the "tertiary sector" and include administration buildings of industrial business corporations. Few statistics broken down into consumption categories are available for this sector.

[39] That is, if the current crisis does not have long-lasting negative effects on economic performance and reduces energy consumption as a consequence.

[40] VDE (Verband der Elektrotechnik, Elektronik und Informationstechnology; Association for Electrical, Electronic & Information Technology): Efficiency and energy saving potential of electric energy in Germany (2009)

taking into account an assumed further increase in efficiency by 20%. Avoiding, or even reducing, this increase in energy consumption, as planned by the German Federal Government, would require many more additional measures than those planned today.

Other scenarios are also conceivable as shown by other studies. The ECCP[41] has analysed production processes in different branches of industry and concludes that savings of about 25% (10% - 40%) are possible within the current technological framework, showing some differences between the total final energy consumption and electricity consumption. Reaching the goal of saving 20% of the total energy in the industrial sector by 2020 appears to be overall realistic[42] in view of these analyses if the necessary framework conditions for their cost-effectiveness can be provided. The current crisis will have a positive effect on energy consumption at first, but it might also, in view of a possibly slightly reduced pressure on energy cost in the medium term, negatively affect the willingness of the industry to invest and introduce technologically-possible improvements in efficiency.

1.4 Energy-saving potential

Extrapolating the expected future use of electric energy and the possible saving effects is very difficult and complex as the analysis needs to be broken down into various individual aspects if credible statistical assertions are to be made. Individual studies of the different sectors document various ways of reducing the final energy of the private households, BTS and industrial sectors and point out that the medium-term political goal of improving energy efficiency by 20% should be reachable. Tab. 3[43] gives examples of several areas for easy-to-realise savings as well as figures for ambitious reductions to achieve the short-term target of 2015. The data have been adjusted for Germany according to figures of the European Union. The costs of CO_2 avoidance and higher costs of fossil fuels may have a positive effect on the energy saving efforts of all sectors.

Selected Areas	Consumption (2005) (TWh[44])	Likely savings (TWh)	Ambitious goals (TWh)
Hot water generation in households	12.6	0.6	3.9
Office equipment	11.6	1.9	3.9
Standby losses	8.5	3.9	5.8
Household lighting	18.4	2.0	5.4
Household appliances (washing, dishwashing, cooling, cooking …)	32.0	8.5	11.6
Electric engines	137.1	11.6	38.8
Lighting in the commercial sector	35.9	7.0	14.0
Total	**256.2**	**35.5**	**86.5**

Tab. 3: Short-term savings potential of electric energy as opposed to a "business as usual" scenario for some areas (by 2015)[45]

41 European Climate Change Programme, http://ec.europa.eu/environment/climat/eccp.htm

42 Source: Ecosys2000, citing the ECCP report

43 In order to accomplish these ambitious goals, quite significant attitude changes would need to be expected of the population.

44 1 TWh = 1000 GWh = 1 billion kWh

45 Figures for Germany calculated on the basis of: P. Bertoldi, B. Atanasiu, Electricity Consumption and Efficiency Trends in the Enlarged European Union. Status Report 2006, JRC IES 2007 EUR 22753 EN

Europe's political goal of 20/20/20 (see footnote 7) addresses savings in all sectors and for all types of final energy. Electricity, a high-quality and flexibly usable type of energy, usually shows an unsurpassed overall degree of efficiency where mechanical energy is the final application. If thermal energy is the final use, direct combustion of fossil and renewable fuels can be advantageous in terms of its effect on the climate and with regard to primary energy use provided a high temperature in comparison to the ambient temperature is required; in all other cases, electrical heat pumps are superior. However, if a power plant runs on fossil fuels, extensive CO_2-free electricity generation is not possible. In the foreseeable future and under framework conditions currently proposed (see chapter Fossil-Based Power Plants), the goal of reaching economically minimal CO_2 emission rates from fossil-based systems by using CCS can only be realised in large central power plants. This is going to have an effect on the competition between electricity and the decentralised use of fossil fuels. For this reason, it is expected that electricity consumption will continue to increase across Europe including Germany. The study by the VDE[46] is worth mentioning in this regard; it projects that German electricity demand will increase from 518 TWh (2005) by nearly 30%, i.e. by 1.3% per year, to 670 TWh in 2025 – in spite of the various energy saving measures that are being discussed. According to the study, without energy saving effects, an increase to 780 TWh (+48%, i.e. 2.2% per year) could be expected.

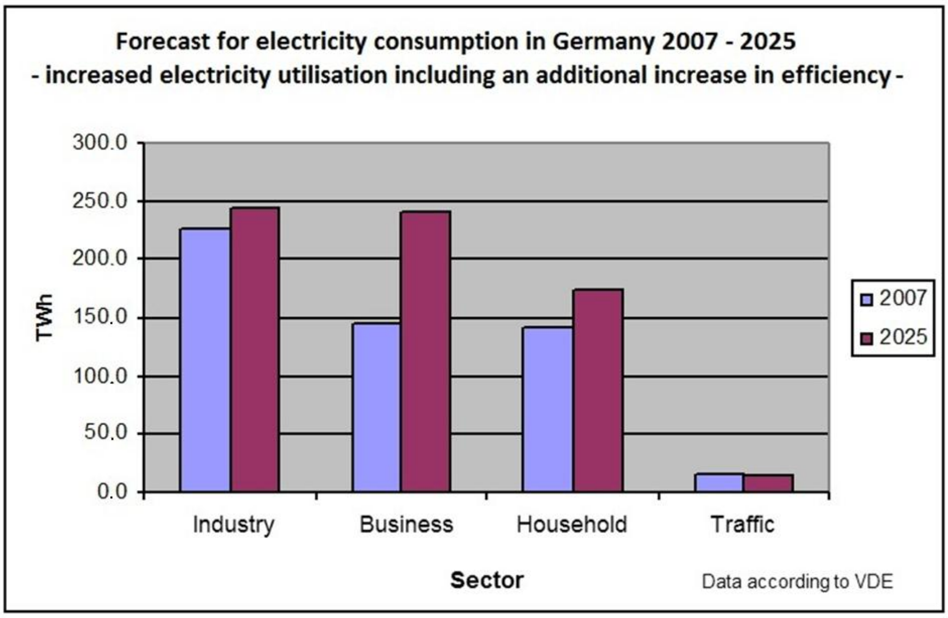


Fig. 3: Projection of electricity consumption in Germany 2007-2025

With regard to the individual sectors, the study estimates an increase of 0.6% per year for the industrial sector and 1.7% per year for the private households sector (see Fig. 3). The lion's share of the increase, however, is expected to take place in the BTS sector, at nearly 4% per year. For the transportation sector it is hoped that the comparatively low electricity consumption may even be reduced by 0.8% p.a. using more efficient railroad systems; however, the possible large-scale introduction of electric road vehicles needs to be considered: it might increase consumption significantly (see chapter I.3 *Transportation - Electromobility*).

[46] Effizienz- und Einsparpotentiale elektrischer Energie in Deutschland. Perspektive bis 2025 und Handlungsbedarf. (German only; translation: Efficiency and Energy Saving Potential of Electric Energy in Germany. Projection Up Until 2025 and Need for Action.) Study by the Energietechnische Gesellschaft (ETG; Power Engineering Society) of the VDE (Verband der Elektrotechnik, Elektronik und Informationstechnology; Association for Electrical, Electronic & Information Technology), March 2008

I.2 Thermodynamically optimised heating

2.1 Exergy necessary for heating

2.1–a The term exergy

There are various types of energy. Electric energy and heat are not at all equivalent, however: Electricity can be converted fully into heat – the reverse, unfortunately, is not the case. Even using an ideal heat engine, only the part of a given heat quantity called “exergy” can be converted into electricity. “Exergy”, in this context, is initially simply a new and handy term for “technical working capacity” or “available work”. Even an ideal heat engine must emit residual heat as “anergy” to the environment, at the ambient temperature T_A.

The amount of producible exergy ΔE (e.g. as electric energy) from a heat quantity ΔQ depends simply and solely on the working temperature T of the heat extraction and on the ambient temperature T_A for the absorption of residual heat (i.e. anergy). This is described by a fundamental equation [1] where the prefactor is called the Carnot factor (temperatures refer to absolute zero -273°C, i.e., they must be entered in Kelvin):

(1) $$\Delta E = (T-T_A)\,/T \;*\; \Delta Q$$

A numerical example: From a heat reservoir of T = 90°C an ideal heat engine which emits its waste heat at a cooling water temperature T_A = 30°C is able to generate, in theory, that amount as electricity (i.e. as pure exergy) corresponding to a Carnot factor of 0.17. The remaining 83% of the energy applied occurs as entirely useless anergy. In practice and for technical reasons, perhaps only about 60% of the potential of an ideal engine can be realised; in other words, one must be content with a degree of efficiency of about 10% instead of 17%.

In the case of an ideal (reversible) engine, equation (1) can be read in reverse

(2) $$\Delta Q = T\,/(T-T_A) \;*\; \Delta E$$

and an ideal heat engine becomes an ideal heat pump: through the input of, for example, electric energy ΔE, one can pump such an amount of ambient heat to a higher temperature T that a total heat quantity ΔQ – which is greater than the applied exergy ΔE by the reciprocal Carnot factor $T/\,(T-T_A)$ – is reached at this temperature level. The reciprocal Carnot factor represents, with regard to a given temperature level of the heating system, T, and the ambient temperature, T_A, a maximum leverage for the thermodynamic generation of heat from electricity (in our numerical example above, this leverage is 1/0.17 = 6).

2.1–b The three approaches to thermodynamically optimised heating

During simple heat generation by mere combustion, it is at least seen to today that all heat is integrated into the heating process. Applying exergy (e.g. electricity), useless ambient heat can be pumped using a significant leverage to a higher temperature level for heating purposes. Instead of burning fuel directly, it can be used for generating electricity. Heating, generating and using electricity must therefore be viewed in a broad integrated context. In this regard, exergy is the relevant thermodynamic controlling factor. A heating process intended to leave no amount of exergy unutilised is termed “thermodynamically optimised heating”. There are three approaches to this:

(1) Anergy itself is useless – ambient heat is always available anyway. If waste heat is not emitted as pure anergy during electricity generation, but already transferred to a refrigerant above the ambient temperature T_A, the result is a lower electricity yield, but the heat, given proper adjustment of the discharge temperature T, can be used for heating purposes, for example. This is the fundamental idea of combined heat and power generation. Combined heat and power generation is the first approach to thermodynamic heating.

(2) Using a heat pump, anergy, i.e. a heat quantity ΔQ_A at a temperature T_A, can be extracted from the environment, pure exergy in the form of mechanical or electric energy ΔE can be added, and the heat quantity ΔQ can then be used at a higher temperature level for heating purposes, for example. The heat pump process is the second approach to thermodynamic heating.

(3) During heat transfer a certain amount of exergy is always lost since the heat source must, as a basic principle, always be warmer than the heat sink. However, thanks to technology such temperature differences can be reduced. Working with small temperature differences, therefore, is the third approach to thermodynamic heating. It is realised mainly by surface heating (floor and panel heating).

2.1–c Exergy necessary for heating

Operating a residential building requires three basic thermal services:

(1) Supplying thermal heat in order to compensate for transmission losses Q_T, in particular – depending on the insulation standards and requirements of the residents – from about the beginning of October until April in order to maintain a temperature level of about 18°C to 20°C during usage times. At night, a lowering of the temperature is acceptable, something which can be achieved in the most energy-efficient way by turning off the heat generator at night-time.
(2) Generating air infiltration heat Q_I in order to warm up fresh air from the outside temperature ($T_{outside}$, 1-2°C on average) to room temperature (T_{room} = 20°C).
(3) Supplying warm water heat Q_W to warm up drinking water from the cold water temperature T_{CW} (about 15°C) to hot water temperature T_{HW} (about 50-60°C) year-round, either using a continuous-flow heater or a hot water tank.

The energy service thus comprises a process of maintaining temperatures (indoor temperature control) and two processes of warming-up (hot water and fresh air). A minimum input of exergy can be calculated for each of these tasks.

However, to date, fresh air is warmed up to room temperature only very rarely using the counter current process; most of the time, the warming-up of fresh air is caused by cold outer air entering the room near the radiator and mixing with the ambient air and warming up on the interior walls. With regard to hot water supply, the exergetic advantages of a warming-up process (including gliding temperature of heat transfer) are also used only rarely; hot water is mainly supplied by the space heating system.

The ideal exergy requirements for the heating of a building with two different types of heating systems are shown in Tab. 1. The “ideal heating system” fulfills the basic thermal services described above with the theoretically minimum effort, something that is, of course, in practice, only possible in approximation. The “ordinary heating system” generates all of the required heat in one central space heating system and transports it to the rooms via heating circuit water at a radiator temperature of 50°C to be used simultaneously as transmission heat and air infiltration heat; hot water generation also takes place directly at 50°C, i.e. without utilising a gliding warming-up.

Temperature of heating surface			Ideal heating system 20 °C		Ordinary heating system 50 °C	
Heating-up utilised			**Yes**		**no**	
	Shares	**Energy [MWh] thermal**	**Exergy factor, ideal**	**Exergy [MWh] electric**	**Exergy factor, ideal**	**Exergy [MWh] electric**
Heating	0.4	40	0.068	2.7	0.155	6.2
Ventilation	0.4	40	0.034	1.4	0.155	6.2
Hot water	0.2	20	0.062	1.2	0.124	2.5
Total		**100**		**5.3**		**14.9**
Exergy leverage ("performance factor")			**18.7**		**6.7**	

Tab. 1:
Ideal conversion factors exergy/energy ("exergy factor") for the three basic thermal services during thermodynamically optimal heat supply for a building with a total yearly heat demand of 100 [MWh]$_{th}$.
The ratio of heat energy to exergy is termed exergy leverage or performance factor (calculated for T_{HW} = 50°C, $T_{outside}$ = 0°C; for details regarding the calculation of figures see /Materialienband ("materials volume") I.2/).

Through a comparison of the required exergy input into the "ideal heating system" and the "ordinary heating system" – summed up in the respective exergy leverage – the importance of an optimisation in terms of heating technology through a separate warming-up of fresh and hot water and through surface heating systems with low inlet temperature becomes apparent. The ideal optimisation in terms of heating technology nearly triples the exergy leverage (Tab.1) compared to the "ordinary heating system" and thus would use just a third of the exergy (e.g. electric energy). The exergetic potential for heat generation, for example, using heat pumps can only be fully utilised if thermal renovation and possibly an adjustment of the heat generator is combined with (or takes place prior to) the replacement of the heat generator. In that case, the inlet temperature may remain below 30°C.

2.2 Sources of heat energy and their exergy content

Tab. 1 shows that only a low exergy percentage of energy is required for the heat supply of a building; these low requirements are fully utilised during thermodynamic heating. During mere combustion of oil and natural gas or even direct electrical heating exergy is wasted instead.

Direct electrical heating can only be tolerated nowadays, if

- a complex heating system proves to be inappropriate and thus uneconomical because of a radical decrease in heat demand, or
- the direct use of electricity as fuel only compensates for a loophole or supply shortfall.

<u>2.2–a Mere combustion</u>

Today, direct heating using natural gas or oil is still more common. Combustion takes place at high temperatures and heat energy is transferred by thermal radiation and cooling of the initially very hot exhaust gas onto the heating medium water which, however, does not actually require high temperatures. The exergy waste thus takes place on the high temperature side of the boiler.

In a modern condensing boiler operating a surface heating system (floor and panel heating), the cooling of the exhaust gas occurs down to the condensation area and at any rate here, that is at the cold end of the heating system, the exergy loss during heat transfer onto the heating circuit water is very low and satisfactory even from an exergetic point of view .

2.2–b Electricity heat coupling during electricity generation: CHP

In a combustion engine, the exergy of the applied heat is at best converted into electricity. The unavoidable anergy and technical losses of the power engine are emitted to the environment as heat. So what is more obvious then, than to emit this “waste heat” already at a higher temperature level; and not to emit it as waste into the environment but apply it as useful heat for heating purposes, for hot water generation or as process heat for industrial purposes. Thus the cooling medium with the lowest available temperature (e.g. river water, outside air) is replaced by a technical “environment”, a heat sink at a sufficiently high temperature level whose cooling heat can still be used as a heat source for thermodynamically less demanding processes. This cooling heat still contains some residual exergy which, naturally, is therefore not available for electricity generation. Under ideal conditions this residual exergy would just be sufficient to drive an ideal heat pump (see next subchapter) which generates the same useful heat with regard to amount and temperature. Cogeneration (CHP), in principle, is thus a very elegant way of optimally meeting a given electricity and heat demand simultaneously and theoretically.

In practice, however, there are serious limitations in terms of technology and energy economics. The theoretical advantages of CHP do not generally justify regarding CHP as the optimal solution for electricity and heat supply. A more detailed study for each individual case is required (see chapter II.3).

2.2–c Electricity heat coupling during electricity use: heat pump

In a combustion engine driving an electricity generator, a large part of the exergy content of the fuel is transferred to the product “electricity”, even under practical conditions. In the other direction, using electricity, processes may be realised in which ambient heat, i.e. pure anergy, is being “pumped up” to a temperature sufficient for heating. Since electric energy consists of pure exergy, the amount of exergy calculated for various heating purposes in subchapter 2.1-c is to be understood as the minimum input of electricity of the “ordinary heating system” into the running of this “heat pump”.

An economic heating system using heat pumps, therefore, should meet two goals:

(1) The “heaters” need to be planned in such a way that heat transfer can take place with as little exergy loss as possible, i.e. with a small temperature difference. This is achieved in well thermally insulated houses using large-surface heaters.

(2) The heat pump itself must be highly efficient. This means:
- The compressor should have a high electric degree of efficiency so that the exergy of the electric energy can be found, preferably undiminished, in an increase in exergy of the working substance (i.e. the “refrigerant”) of the heat pump.
- The temperature differences between the ambient heat, or the inlet temperature of the heating system, respectively, and the working substance of the heat pump should be small.
- The input of auxiliary energy, for instance into pumps or blowers for the heat exchangers, needs to remain low.
- The material properties of the working substance should provide a good approximation for an optimal thermodynamic process (e.g. “Carnotising”).

- The working substance needs to have particular properties which allow for a temperature glide and thus the lowest possible temperature difference across the entire temperature region which is covered during the warming-up of the heating-circuit water and particularly during heating-up processes (fresh air, hot water).

The ideal heat pump, which absorbs heat without loss at an ambient temperature T_A and emits useful heat Q at a higher temperature T by the use of exergy (e.g. electric energy) E, has, according to equation (2), a coefficient of performance which corresponds to the inverted Carnot factor. In practice, technical curtailments must be made; they can be correlated with the requirements for “high efficiency” mentioned above and can be described, in summary, by the introduction of three parameters:

f Quality factor which takes into account the degree of efficiency of the compressor of the heat pump and the imperfect thermodynamical cycle.

ΔT_{ob} Temperature difference at the liquefier between the working substance of the heat pump and the inlet temperature of the heating-circuit water (i.e. the final temperature of the warmed up heat carrier).

ΔT_a Temperature difference between the available ambient temperature T_A and the boiling temperature of the working substance of the heat pump at the evaporator.

In addition, there is the energy expenditure E_e for pumps, control and, if necessary, for an electric heating rod serving as bottleneck heating which, however, is included in the quality factor f most of the time. Considering these technological limitations, instead of equation (2) one has:

(3) $$Q = f * (T + \Delta T_{ob}) / [(T - T_A) + (\Delta T_{ob} + \Delta T_a)] * E$$

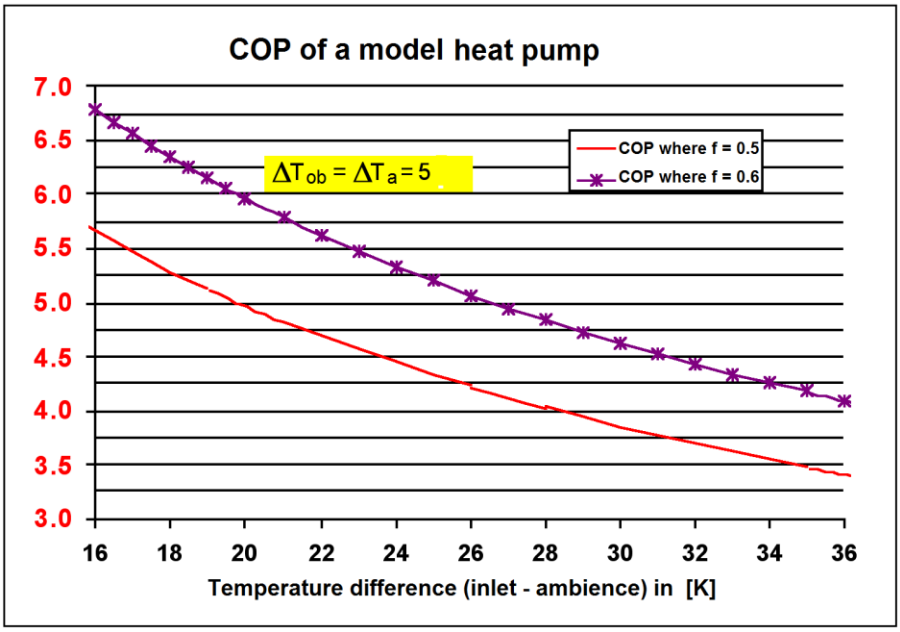


Fig. 1:
Coefficient of performance (COP) of a heat pump according to equation (3) with an upper and lower temperature difference of 5 K each with regard to the working substance for two practical quality factors *f*.

In Fig.1, the coefficient of performance of a model heat pump described by equation (3) as COP = Q/E is shown as a function of the temperature increase between the ambient heat (as a heat source for the evaporator) and the inlet temperature of the heating system. At the heat exchangers a (somewhat ambitious) temperature difference of $\Delta T_{ob} = \Delta T_a = 5$ [K] was assumed. It becomes apparent that, using relatively low inlet temperatures, as is possible in well thermally insulated houses with surface heating and appropriate source media (e.g. soil or ground water, or even outer air with ice storage), high coefficients of performance above 4 or even 5 are possible.

There are many types of heat pump systems varying according to:

- Ambient heat reservoir:
  ground (near surface brine/soil collector, brine/soil probe down to a depth of 100 m),
  water (ground water, bank filtrate),
  air (outer air directly or through an underground intake pipe).

- Required inlet temperature:
  At 50-60°C and higher: Mere replacement of old firing systems without thermal renovation of buildings;
  At 40-30°C and lower: New buildings with surface heating, old buildings after thermal renovation and installation of surface heating.

- Heat storage units: Bridging very cold days with the help of heat storage units for ambient heat (e.g. ice storage) would help to optimise the use of air-heat pumps.

In practice, the current coefficient of performance of a heat pump is not of greatest importance but rather its seasonal performance factor, usually averaged during the period of one year, which is defined as the ratio of emitted heat to total electricity input: The achievable performance factors depend, of course, on these variations and the specific case. Russ et al. [2] have presented a comprehensive study on the use of heat pumps in the thermally non-renovated building stock. Various heat pumps of up to 20 kW heating power from a total of 13 manufacturers were used in the field test.

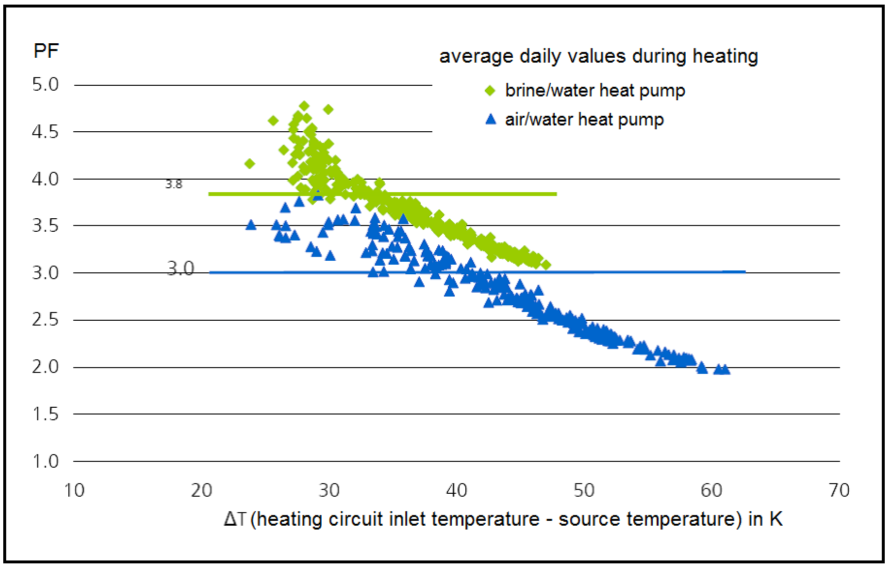


Fig. 2:
Performance factor (PF) of air/water heat pumps and brine/water heat pumps during heating time (only heating) as a function of the temperature lift ΔT of the heat pump, on the basis of daily averages (period 11/07-10/08) [2]

In Fig. 2, the average daily figures of the performance factor (PF) are shown as a function of the temperature lift ΔT between the inlet temperature of the heating circuit (T in our nomenclature) and the source temperature T_A for the mere heating process (that is, excluding hot water generation). It becomes apparent that:

- Heat pumps using a liquid as the heat source have considerably better performance factors than those using air.
- Performance factors averaged over a year were quite good, even for the unfavourable case of “thermally non-renovated old buildings with radiator heating” where they reached values of 3.8 for brine heat pumps and 3.0 for air heat pumps.
- Performance factors for small temperature lifts of about 25 to 35 K are between 4 and nearly 5 for brine/water heat pumps.

To achieve a final solution to heating buildings it is insufficient to be content with a change in energy supply. Prior thermal insulation (if feasible) is indispensable, and in many cases this will include a changeover to surface heating. In that case, however, Fig. 1 and Fig. 2 already show that the heat pump will presumably be able to come up with performance factors of nearly 5 and even better in the future for the low temperature lifts ΔT expected. – In summary, one may conclude that for strategic considerations it is justified to assume a high performance factor for heat pumps.

2.2–d Engine heat pump and gas absorption heat pump

There are heat pumps whose exergetic drive is provided locally without detouring via the power grid and would hence require less ambient heat than an electric heat pump when operating at the same performance factor of primary energy:

- When operating an engine heat pump, the engine waste heat is also used for heating purposes, e.g. a gas engine drives a heat pump directly.
- When operating a gas absorption heat pump, the function of the compressor in the heat pump process is replaced with a thermally driven solvent circuit. A part of the exergy of the heat source is utilised, therefore, for the mechanical work of compressing the refrigerant.

2.3 Optimisation of building insulation and heat supply

Wasteful heat demand and heat supply from simple combustion can no longer be tolerated with regard to buildings. The “warm house” energy service must and can be achieved by energetically and exergetically optimised, i.e. “thermodynamic”, heating. To achieve this it is necessary that:

- the transmission heat requirement is drastically reduced through constructional measures and a large part of the air infiltration heat needs to be recovered through fresh air to exhaust air heat exchangers,
- thermal solar energy is used for hot water generation (particularly in summer) and for heating during the transitional period and partially in winter as well,
- the residual demand for thermal heat is provided using exergetic optimisation and in the context of energy economics, and
- the transfer of thermal heat to heat the building and to warm-up fresh air and service water takes place without avoidable exergy loss.

The expected energy price increase will extend the scope for technical design and improvement. The concept of the “passive house” [3] has already shown a trend-setting and practical method for new buildings which may also be applied to old buildings. Thermally insulating buildings is a cumbersome and long-winded process and should ideally take place, for financial reasons, during a general renovation or a replacement investment that need to happen anyway. There are two competitors in the field of thermodynamic heat supply: CHP and heat pumps. They will be compared with regard to their energy saving potential in chapter II.3 *Combined Heat and Power Generation and Systems Comparison*.

2.4 Summary and outlook

The "warm house" energy service can only be provided by an integrated concept using minimal primary energy. After thermally insulating buildings (including designing the heating surface for low temperatures) and utilising free energy sources such as solar energy and waste heat, the remaining heat energy demand is very low in terms of quantity and quality (temperature requirement, exergy) and can be well met by heat pumps. Of the total German gas sales of 925 TWh in 2007, 11.5% was used for conversion into electricity by power plants and 27% mainly for heating purposes in households. If heat pumps become widely accepted in many areas, gas supply could be abandoned in these areas on a large scale and used for electricity generation thus enabling the expansion of the environmentally-friendly and effective conversion of gas into electricity by the transition to thermodynamically-opitmised heating.

Notes and references

This chapter is based both on a comprehensive presentation as an "encyclopedia of materials" (Materialienband) and a power point presentation in which further details are provided.

Gerhard Luther: Materialienband (encyclopedia of materials), *Thermodynamisch optimiertes Heizen* (German only; translation: *Thermodynamically Optimised Heating*)
http://www.uni-saarland.de/fak7/fze/AKE_Archiv/DPG2010_E-Studie/

Gerhard Luther: *Thermodynamisch Optimiertes Heizen* (German only; translation: *Thermodynamically Optimised Heating*), http://www.uni-saarland.de/fak7/fze/AKE_Archiv/AKE2009F/Links_AKE2009F.htm

Further works:

AIP Confernce Proceedings Nr.25: *Efficient Use of Energy*, American Institute of Physics (AIP), New York (1975), ISBN 0-88318-124-X

J. Fricke and W.L. Borst: *Energie – Ein Lehrbuch der physikalischen Grundlagen* (translation: *Energy – A Textbook of Fundamental Physics,* in 2011 a revised English edition will be published), R.Oldenbourg Verlag, Munich (1981), ISBN 3-486-24971-1

[1] A simple derivation from the two main theorems of thermodynamics in the encyclopedia of materials, loc. cit.

[2] Christel Russ, Marek Miara, Michael Platt: *Untersuchungen zum Einsatz von Wärmepumpen im Gebäudebestand*, (German only; translation: *Studies of the Application of Heat Pumps in Buildings*), Fraunhofer-Institut für Solare Energiesysteme (Fraunhofer Institute for Solar Energy Systems) Freiburg (2009), fig. 10, p.10

[3] Wolfgang Feist: http://www.passiv.de/

I.3 Transportation – Electromobility

3.1 Introduction

Mobility is an extremely desirable commodity for most people. The traffic volume of private transportation on land[1] has increased accordingly in the industrialised countries in recent years but is, however, approaching saturation in many cases.[2] In countries such as China or India, motorisation is just at the beginning of a rapidly increasing development.[3]

Today, worldwide traffic already accounts for 20% of energy-related greenhouse gas (GHG) emissions [4] and 24% of CO_2 emissions [5]. In the EU, 71% of the overall traffic (and even about 97% of road traffic) depends on mineral oil and is responsible for about 20% of the total CO_2 volume [6].

It is a tantalising idea, therefore, to avoid the harmful effects of traffic by its electrification (catch-phrase "electromobility")[4]. Replacing the "resource oil" with the new "resource electricity" not only eliminates the dependence on oil but also avoids harmful CO_2, provided that electricity is supplied by CO_2-free sources. The advantages of electrification are of an ecological (reduction of CO_2 and pollutant emissions), economical (oil price increase, oil shortage) and political (less dependence on oil imports, accelerated introduction of renewable energy sources) nature.

The electric car has therefore become a hot topic of public and political debate. This great interest in the battery-powered electric drive is primarily based on its high degree of efficiency (typical efficiency factor of vehicles of 70% to 80% as compared with the combustion engine's 20% to 28% and the fuel cell electric drive's 40% to 50% [7]) and on the prospect of having the batteries powered by CO_2-free electricity. The latter leads to a close mental association between "electromobility" and "renewable energy sources". The same association results from the future vision of utilising electric cars as part of an "intelligent" grid as storage units for the fluctuating supply of "renewable energy" from wind and sun (see subchapter 3.3-b).

Figure 1 shows the very low CO_2 and pollutant (NOX) emissions of future electric vehicles compared with the emissions of current "conventional" petrol and diesel cars.

The long-term replacement of all petrol and diesel cars with electric cars is part of a worldwide strategy to restrict climate-harmful GHG emissions. Whether electric vehicles will be able to meet these expectations and how long it will take to get there is above all an economic-technological question, i.e., if and when suitable batteries can be produced. Adequate political framework conditions are a necessary requirement in this regard but no guarantee for success. The German Federal Government has recognised the great strategic significance of electromobility and has set itself ambitious goals with the "Nationaler Entwicklungsplan Elektromobilität" (National Electromobility Development Plan) of August 2009 [8]: It intends to boost research and development, market preparation and market introduction of battery-powered electric vehicles in Germany and make Germany the leading market for electromobility. It intends, therefore, to have one million electric vehicles on Germany's roads by 2020 and to have an area-wide car-charging infrastructure for metropolitan areas.

---

1 Air traffic will not be discussed here. The emissions it causes currently account for 3-4% of the total GHG emissions but, according to the ICPP, could increase to 15% by the year 2050 due to increasing air traffic [1].

2 In Germany, for example, the saturation figure is about 45 million passenger cars [2].

3 In India and China alone, an additional 155 and 210 million cars respectively are expected by the year 2030 [3].

4 Electromobility, in combination with renewable energy sources, is aimed at making a significant contribution to the implementation of the climate protection targets of the German Federal Government and, accordingly, is firmly established in Germany's "Integriertes Energie- und Klimaprogramm (IEKP)" (German only; translation: "Integrated Energy and Climate Programme").

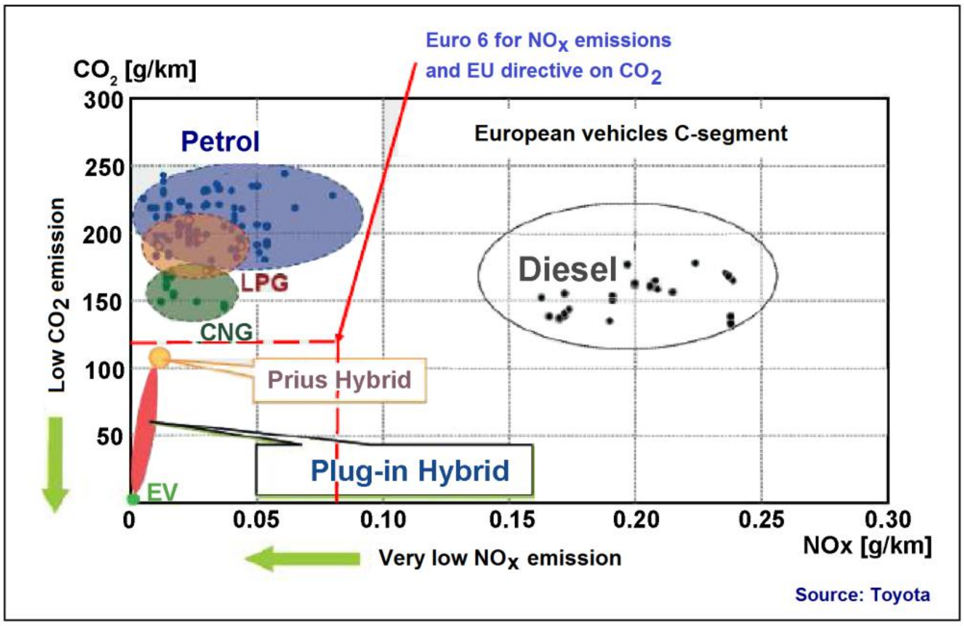


Fig. 1: CO_2 and NO_x emissions of future electric vehicles compared with current "conventional" petrol and diesel cars (from [7]). The "Prius III Hybrid" car already available on the market has been certified at just 89gCO_2/km [9].

While there is largely agreement that the future belongs, in the long run, to the "true" electric car (battery-powered electric vehicles and "plug-in" hybrid vehicles) fuelled by CO_2-free electricity, no one can say at present how long it will take for this development to dominate the market. The car manufacturer Toyota estimates a period of about 20 years which seems to be in agreement with the opinion of most of the international car companies.

In the following subchapter we will briefly discuss *public transportation (mainly rail transportation)* before turning our attention to the main topic, the electrification of *private transportation*, in other words the electric car. Focusing on the electric car is justified simply by the fact that private transportation outnumbers public transportation – and thus is of far greater overall economic importance – in Germany currently by a factor of five or six (see Tab.1).

Motorised private transportation	880				
Public transportation	162				
Of which:		Railway* in total	82		
		Of which:		Short-distance traffic (SDT)*	46
				Long-distance traffic**	36
		Bus, occasional traffic	27		
		Public SDT road	37		
		Public SDT rail**	16		
Total	1,042				

*already largely with electric traction; ** already mostly with electric traction

Tab.1: Traffic volume of ground traffic in Germany in 2008 (in billion passenger kilometres) [2]

3.2 Public transportation

Electrification has made the most progress in the area of public transportation which to a large extent (about 60%) takes place in the form of railway transportation in Germany and is mostly (about 90%) electrified (see Tab. 1). Accordingly, the specific CO_2 emissions of the Deutsche Bahn (DB) AG's railway transportation (based on data from 2008) are much lower (76 and 46g CO_2/Pkm for short-distance and long-distance traffic respectively) than those caused by road traffic (134 and 138g CO_2/Pkm for short-distance and long-distance traffic respectively) [11].

In other words, electric traction already dominates long-distance railway traffic in Germany today and, accordingly, the specific CO_2 emissions are moderate. The relatively high "climate quality" of traction power (more than 40% generated CO_2-free), however, mainly results from the use of nuclear energy (about 70% of the CO_2-free electricity share is generated by the nuclear power plant Neckarwestheim) [12] and will most likely fall off without nuclear energy in the future[5]. Despite all that, the Deutsche Bahn (DB) AG has set itself ambitious CO_2 reduction targets[6].

While long-distance rail traffic has been almost completely electrified, the worldwide trend of electrifying public transportation as well has been mostly ignored in German cities. In many industrialised countries (e.g. France, Spain, Great Britain) there has been, for various reasons (transportation safety, reduction of particulate matter emissions, town centre revitalisation, amongst other things), a renaissance of the tram – it is much more economic than busses and more cost-effective than building new underground lines. In German cities, however, trams have been mostly done away with.

These examples from abroad ought to make it apparent to those responsible in Germany what can be achieved when proper framework conditions are set. Proposals have been made which are aimed at vast rail traffic growth: the German coalition contract declares a "Deutschlandtakt" (synchronised timetable for Germany)[7] and the president of the "Bundesarbeitsgemeinschaft der Aufgabenträger im Schienenpersonennahverkehr (BAG-SPNV)" has formulated the goal of doubling rail traffic demand in the next couple of years [14].

3.3 Private transportation – the electric car

Let us now turn our attention to private transportation and the electrification of vehicle engines. We focus, according to the subject matter of this study, on electric vehicles with drive concepts featuring a high share of electricity, such as:

- *electric vehicles powered solely by batteries* (battery electric vehicles, or BEV), and
- *plug-in hybrid electric vehicles*, or PHEV, featuring a combination of an electric and a combustion engine and a larger battery (than those used in a pure hybrid) which can be charged via the grid[8].

---

[5] According to the current plans of the DB AG (Deutsche Bahn AG; the German national railway company), nuclear generation of electricity is to be replaced by electricity from coal should the nuclear power plant Neckarwestheim be shut down [12].

[6] From 1990 to 2008, the DB AG (Deutsche Bahn AG; the German national railway company), has reduced its specific CO_2 emission caused by railway transportation by about 40% (by using electricity generated by nuclear power plants). Its new goal is to reduce the specific CO_2 emissions of the entire company by 20% between 2006 and 2020 [13].

[7] The new German coalition contract contains the promise to carefully examine proposals for the introduction of a "Deutschlandtakt" (synchronised timetable for Germany) for public railway transportation in cooperation with the German federal states.

[8] Plug-in hybrid vehicles combine the advantages of battery-powered and petrol-powered vehicles (although they incur the disadvantage of higher manufacturing costs): The vehicles run silently and emission-free for short distances and in local traffic using an electric engine while the second engine (combustion engine or fuel cell system) extends the range of the car. Parts of the German automobile industry are pursuing the concept of a "Range Extender" based on fuel cells.

Although the combustion engine is going to continue to dominate traffic for the foreseeable future and increase its environmental compatibility by increasing its efficiency and using biogenic fuels, it is necessary to forcefully initiate the transition to electric vehicles right now. The required technologies (electric drives, electric energy storage cells, necessary grid infrastructure, amongst other things) are available in their basic form but need to be significantly improved and developed further for large-scale use at market-economic conditions.

In the following subchapters we will discuss the most important issues relevant for the evaluation of the future development of electric vehicles, i.e. their energy efficiency, their potential for CO_2-reduction, their additional energy demand, their possible application for load management and, last but not least, the development of suitable electric batteries.

3.3–a Energy efficiency and CO_2 reduction

Energy efficiency: comparison of electric and diesel vehicles

When discussing the energy efficiency of a vehicle, the various levels of energy utilisation, from the vehicle's effective energy via its final energy and up to its primary energy need to be taken into consideration. In doing so it becomes apparent that the different steps of comparison may yield very different comparative figures. This will be illustrated by comparing the specific energy consumption of a battery-powered electric vehicle with a diesel passenger car, as demonstrated in [15].

	Diesel vehicle	Electric vehicle
(1) Effective energy demand [kWh/100 km]	11	11
(2) Drive efficiency [%]	23	75
1. Step: (1) + losses, f (2) –> (3) Specific final energy consumption [kWh/100 km]	49	15
(4) Utilisation ratio of the provided final energy [%]	88	35
2. Step: (3) + losses, f (4) –> (5) Specific primary energy consumption [kWh/100 km]	55	43
(6) Accumulated energy expenditure [GJ] in relation to 120,000 km lifetime [kWh/100 km]	100 24	180 42
3. Step: (5) + (6) –> (7) Specific total energy expenditure [kWh/100 km]	79	85

Tab. 2: Comparison of the specific energy consumption of a diesel with an electric vehicle

(all figures according to [15])

In this example, a compact car with a demand of effective mechanical energy at the interface tire/wheel of about 11 kWh/100 km (Tab. 2, line 1) was examined. Adding the losses depending on the drive efficiency, the result, in this first step, is the specific final energy consumption. For an electric road vehicle with a drive efficiency of 75% (engine, power electronics and battery) the result is a specific final energy consumption of 15 kWh/100 km[9], whereas for the diesel passenger car with a drive efficiency of 23% the specific consumption is about 49 kWh/100 km (Tab. 2, line 3).

9 No secondary loads, e.g. heating, were taken into consideration here which could be served by waste heat of the diesel engine. Also, mechanic/electric secondary loads, such as lights and air-conditioning, have a higher percentage in a battery-powered car [16].

In a second step, the specific primary energy consumption, depending on the overall utilisation ratio of the provided final energy (electric energy or diesel), was determined. For the electric vehicle, with an overall utilisation ratio of the provided electricity of 35% (which includes the losses in the power plants and transmission grids), the specific primary energy demand is about 43 kWh/100 km; the diesel passenger car, however, has a primary energy demand of about 55 kWh/100 km (Tab. 2, line 5) due to the higher overall utilisation ratio of 88% (which includes the losses in the refineries and the petrol stations).

If the cumulative energy expenditure required for manufacturing a car (here: 100 GJ for the diesel passenger car and 180 GJ for the electric vehicle, including a battery change for the latter during usage of the vehicle) is taken into account in addition to the specific primary energy consumption mentioned above and the cumulative energy expenditure is set in relation to the lifetime of the vehicle (here an assumed 120.000 km), the original advantage of the electric vehicle, based on the favourable drive efficiency, over the diesel passenger car vanishes: the specific overall energy expenditure increases to about 85 kWh/100 km for the electric vehicle, whereas at 79 kWh/100 km it is slightly lower for the diesel passenger car (Tab. 2, line 7).

The purely quantitative assessment of the energy expenditure alone does not do the matter justice, of course, as the quality of the expended primary energy – CO_2-lean energy mix or mineral oil products – is just as or perhaps even more important.

Potential for CO_2 reduction

Electromobility opens up a whole new dimension in regard to the reduction of CO_2 emissions in the transportation sector (cf. Fig. 1): whereas further “conventional” measures for the reduction of energy consumption and thus for the reduction of CO_2 emissions require ever greater efforts, the electrification of drives enables the CO_2-lean handling of traffic at one stroke, given an adequate choice of primary energy sources.

The “carbon footprint” with which an electric car pollutes the environment is the product of its specific final energy consumption (in kWh/100 km) and the specific CO_2 emission (in gCO_2/kWh) which is produced by generating one kilowatt-hour of electricity, using the provided energy mix. That is, it mainly depends on the energy mix that is used to generate the electricity needed for charging the battery. If we take a medium class electric vehicle with a consumption of 20 kWh/100 km for an example and charge it with electricity from the current German energy mix (about 600 g CO_2/kWh), the electricity-related carbon foot print is 120 gCO_2/km.

In contrast, electric vehicles are capable of producing, virtually “over night”, i.e. without further development, considerably less CO_2 in countries having a mostly CO_2-free electricity mix, such as France (80% electricity from nuclear energy) or Switzerland (95% electricity from hydropower and nuclear energy), than the average fleet of petrol or diesel cars would produce. For example, the electric vehicle mentioned above would produce only about 8 g CO_2/km in France [17], in other words one order of magnitude less than in Germany. For the whole of the EU, the carbon foot print of an electric vehicle is 76 g CO_2/km on average [17] and the goal is to halve this figure.

3.3–b Additional electricity demand and load management

Additional electricity demand

As mentioned before, the German government has set ambitious goals for the market introduction of electric cars: having about one million electric vehicles on German streets by 2020[10], and 5 million by 2030, and by 2050 having traffic in cities consist of vehicles that are, for the most part, not powered by fossil fuels.

[10] France actually intends to have 2 million electric vehicles on the road by 2020 and Britain 1.7 million [3].

The additional electricity consumption related to electric vehicles is overestimated in most cases. Assuming an average annual kilometrage of 12,500 km and an energy consumption of 20 kWh/100km of a medium class car as used above, the result is an annual consumption of 2.5 TWh per 1 million electric vehicles which equates to about 0.4% of the annual electricity consumption in Germany (2005: 612 TWh). Only at a comparatively high market penetration of 20% of electric vehicles (about 10 million vehicles) would the additional consumption cause an additional electricity demand of about 4%. The additional electricity consumption of electric vehicles (but also their storage capacity; see below) is therefore of no real consequence for the next 10 to 20 years.

However, as the necessary extension of electric grids and power plant fleets requires considerable lead times (and immense investment), it is necessary to already think seriously now about how a future electricity supply system needs to be structured in detail (particularly in view of a high share of fluctuating renewable energy.

Decentralised mobile electricity storage

Another challenge – as well as opportunity – posed by electric vehicles is their integration into the load management of the energy supply system. If users were to charge their electric vehicles in an uncontrolled fashion, very high additional peak demands would occur in the morning and late afternoon. Therefore, controlling the battery charging process is necessary at a certain stage of market penetration, i.e. an “intelligent” connection of electric vehicles to the grid (the so-called vehicle-to-grid (V2G) technology) [17]. This technology would open the opportunity to use electric vehicles not only as storage units but also for controlling the grid.

Such considerations presume that, in a few years, two trends of development will complement each other and be utilised economically: the extension of fluctuating (and only partially controllable) renewable energy sources and the prevalence of millions of decentralised electricity storage units as part of electric vehicles. As these vehicles are not moved for about 23 hours each day and are often within range of an electric socket-outlet, they could be integrated into a system with fluctuating power feed-in (this vision is the main motivation for the interest of many groups in electromobility: a strong “tandem” of electric vehicles and renewable energy systems).

The nominal storage capacity of 1 million electric passenger cars (goal for 2020) is 10 GWh for an initially realistic storage capacity of 10 kWh/vehicle. This is comparable to the storage capacity of the largest German pumped-storage power plant Goldisthal (8.5 GWh; German pumped-storage power plants overall: 40-50 GWh) and would just be sufficient to buffer the overall current wind power (2009: 25,8 GW) for about 20 minutes. Only if about half (about 25 million) of all passenger cars were powered by electric energy (perhaps by 2050) and their battery capacity had increased to 20 kWh/vehicle (total capacity of 500 GWh) could electric vehicles play an important role with regard to load management.

Controlling power range

While the energy storage potential of 1 million electric passenger cars is relatively low, the vehicles’ capability of controlling power range could be useful already: with connected load of 3 kW, they could, in theory, supply 3 GW of positive/negative controlling power [18] which equates to almost half of the total currently installed power of all pumped-storage power plants (controlling power range 6.7 GW_{el}; controlling energy 7.5 TWh per year) (cf. chapters II.7.1 and III.2.3).

<u>3.3–c The battery – key element of medium-term development</u>

The key element to how quickly the market introduction of electric vehicles will occur is the development of suitable heavy duty/high energy batteries. Currently, lithium-ion batteries are being favoured for use in electric vehicles in the long term as they are the storage system with the highest energy density (see Fig.2). However, further developments still pose a great challenge even with regard to this type of battery. This concerns particularly the required electric storage capacity (6-10 kWh for plug-in hybrids and >20 kWh for battery vehicles), energy density (>500-1000 Wh/kg[11]), lifetime (~10 years, equating to 5000 cycles at 100% depth of charging/discharging), the demanding operating conditions and – last but not least – the costs (<200-500 Euro/kWh) [7,16]. In order to reach these desired target figures, current characteristics need to be improved by factors of 2 to 5. These characteristics will be discussed in the following subchapters.

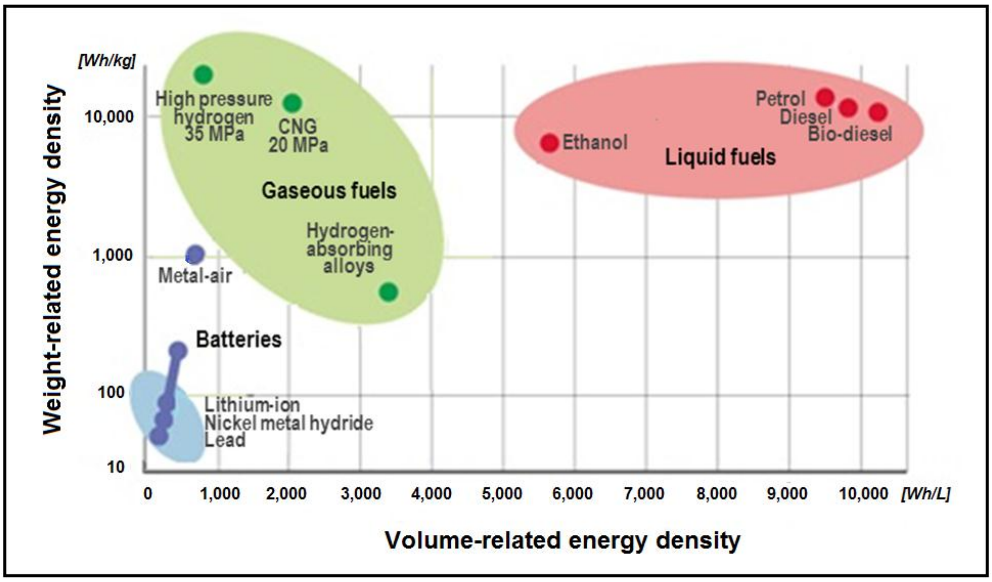


Fig. 2: Challenge for energy density of future batteries (according to [7])

<u>Energy density, storage capacity, range:</u>

The weight-related energy density of Li-ion batteries is currently 130-150 Wh/kg (see chapter III.2.5) and may reach 200-220 Wh/kg within the next ten years[12]. Presuming an energy density of 150 Wh/kg as the current state of technology, the weight of the cells alone is about 200 kg for a medium class Golf-type car (typical consumption of about 20kWh/100 km) and a range of 100 km while the weight of the whole battery system (use of 80% of the nominal energy of the battery, ageing of the battery of 20%, mounting) is about 330 kg [19]. The specific energy densities of current Li-ion batteries, therefore, is still much too low for attractive ranges (>300 km)[13] and needs to be increased significantly. For such ranges, novel types of batteries could be a possibility, such as chargeable metal-air batteries which are capable of providing an energy density of up to 1,000 Wh/kg in extreme cases (see chapter III.2.5). However, at such a high energy density, the issue of safety, which cannot be disregarded even today, takes on an entirely different dimension.

[11] Toyota's long-term goal is 700 Wh/kg as the comparability with current fuels, in particular with regard to range, is then ensured (source [16]).

[12] By way of comparison: a lead accumulator has a specific energy density of about 40 Wh/kg, a nickel metal hydride battery, as currently used in hybrid vehicles, of about 80 Wh/kg (see chapter III.2.5).

[13] In 90% of all cases, the currently available battery capacity represents no actual limitation, however, as the average daily route of a passenger car is merely 30 km [18].

Apart from high energy density, high *power density* is required which allows for fast power output (e.g. during the acceleration process) and fast energy storage (e.g. for recuperation of braking energy). In this regard, heavy duty double layer capacitors (see chapter III.2.4) could prove to be the future solution. To this end, however, their energy density and life time need to be increased and their manufacturing costs reduced.

Cycle stability/life time:

Another important characteristic of batteries is their cycle stability which is essential for the life time and thus the total kilometrage of the batteries. It depends largely on the discharging depth. Due to the high battery costs, it is intended that the life time of the battery corresponds to the life time of the vehicle. Current electric vehicles are designed to have a life time of 8-10 years which equates to a kilometrage of 250,000-300,000 km or about 5,000 operating hours. This means that the batteries need to be able to withstand about 5,000 charging/discharging cycles without significant loss of performance. Cycle stability increases similarly to energy density: from lead (500 cycles) to nickel metal hydride (800 cycles) to standard Li-ion (1500 cycles) and premium Li-ion (2500 cycles) batteries [20].

Safety:

Lithium makes batteries with very high energy density possible but is also very reactive. Therefore, safety of Li-ion batteries needs to be developed further; in this regard, material development and cell design are the best starting-points.

Battery costs:

However, battery costs are the biggest hurdle to a large-scale market introduction of electric vehicles (see Fig. 3).

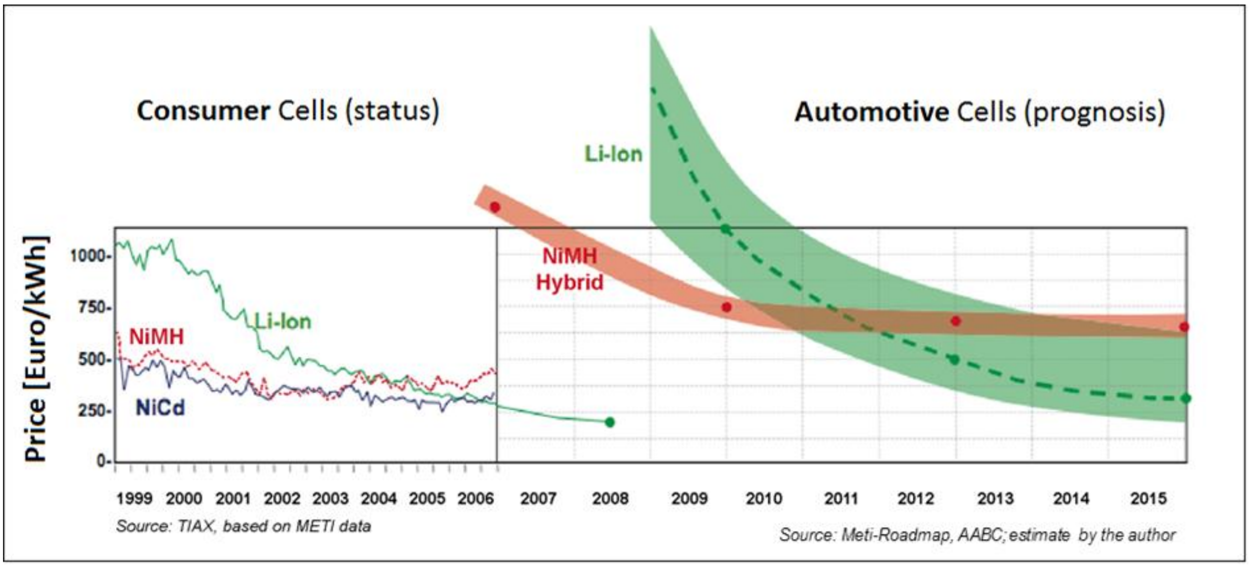


Fig. 3: Costs of new batteries (according to [19])

Currently, they are still at 1,000-1,200 €/kWh, while the cost goal, formulated by international experts, is 200-500 €/kWh and in the long term 200 €/kWh [16]. Small Li-ion consumer cells (e.g. used in laptops), which can be mass-produced today, cost only about 200 €/kWh but the production of automotive fuel cells needed for electric vehicles is still in the test set-up stage) (first serial production about 2009/10, mass production later than 2015) [19]. Costs of about 1,200 €/kWh are estimated for these cells for 2009/10 which may be reduced to 550 €/kWh by 2012/13 and to 350 €/kWh with the start of mass production after 2015 [19].

Availability of battery systems and the required raw materials:
The current state of availability of battery systems for vehicle engines can be summarised as follows [16, 19]:

- Heavy duty batteries for hybrid vehicles: NiMH batteries are already the standard state of technology (although there are basically only two suppliers in Japan), Li-ion batteries however are awaiting or at the beginning of mass production.

- High energy batteries for electric vehicles (plug-in hybrid and true electric vehicles): Currently no product is ready for serial production. Research and (pre)development activities are only under way worldwide, the main focus being Li-ion batteries (which will be introduced to the market in several places in 2010).

Overall, large-scale research and development is required which must build on high-quality basic research (see e.g. [21, 22]). The latter is particularly important in order to find long-term solutions for mass production of, for example, Li-ion batteries that are in accordance with our sustainability standards with regard to the required materials, production methods (eco-efficient processes) and options for disposal. One example of such a solution is the synthesis of organic electrodes produced from natural organic sources by "green chemistry" [23].

The worldwide availability of lithium as feedstock for the production of Li-ion batteries also needs to be discussed in this regard. As detailed in footnote 3 of chapter II.9 on fusion power plants (lithium is one of the two raw fuels for D-T fusion), lithium will not pose a limitation for the use of electric vehicles in the long term.

3.4 Summary and outlook

In principle, the transition to electromobility in the areas of public and private transportation allows for the replacement of the "resource oil" with the "resource electricity" generated, ideally, by CO_2-lean energy sources and which, in practice, is able to utilise the entire spectrum of energy systems as well. The idea is tantalising, killing two birds with one stone: first, *"independence from oil"* – desirable because of the finite nature of oil, its increasing price and its vague guarantee of supply, and second, *suppression of* combustion engine-related *carbon dioxide and pollutant emissions*.

Accordingly, the vision of electric vehicles running on electricity generated by renewable energy sources and which are integrated into an "intelligent" grid in such a way that they can be utilised for storage and control of these fluctuating energy sources, has captivated the imagination of the modern world. Politicians have started to lay the groundwork (laws, financial incentives, amongst other things) for this strategy and the industry is trying worldwide to meet these high expectations.

The technological basis for electric vehicles exists in principle, however all integral components (in particular future batteries) need to be improved by factors of 2 to 5 in order to reach their desired target figures. In particular with regard to energy storage devices it is not clear whether the necessary breakthrough is possible at all. Neither have the safety problems, related to the high technical demands, been solved satisfactorily.

The way to market penetration of electric vehicles solely powered by batteries remains a long one (of at least 20 years), despite great efforts. The transitory period will be characterised by an increasing number of hybrid vehicles – later on plug-in hybrid vehicles – which can provide the experience for the real goal: battery-powered electric vehicles integrated into an intelligent grid.

This transitory period is also sorely needed for the extension of renewable energy systems and the development of an intelligent grid (“vehicle-to-grid” technology), both of which are indispensable for the sensible use of electric vehicles. In this sense, electromobility will initially increase mostly in the area of railway transportation in Germany and other technologically developed countries (adequate framework conditions provided).

Despite the general euphoria over the electric car it must be noted that a significant development potential for energy saving and CO_2 reduction exists for the “conventional” petrol and diesel car as well (estimates assume 20-30% in the coming years) and is being pushed by international car companies in many ways with considerable success: In this regard, the transition to smaller and, in particular, lighter vehicles, the revolutionary engine and gear developments and many more must be noted. This development will and must continue to be executed in parallel to the introduction of the electric car which will later on also profit from this development.

Furthermore it should be noted that many of the big car companies (e.g. Toyota [24]) assume that the fuel cell powered electric engine (cf., for example, [25]) will achieve dominance in the long-distance traffic (>300-400km) – but also here, at the moment, costs are still much too high and a nationwide grid of hydrogen-fuel stations would need to be introduced first.

The transition to a sustainable mobility does not only require technological development but also a new way of thinking. In parallel to technological progress, everybody involved must learn to rethink their ingrained habits with regard to and expectations of traffic: individual driving habits, car sharing, local traffic including electric bikes[14] and electric scooters, better utilisation of public transportation and much more. Only in this way can the transition to climate-compatible transportation and traffic be made within the necessary scope and timescale – and without unwanted discontinuity.

Notes and references:

[1] Nicholas Stern, *The Global Deal – Climate Change and the Creation of a New Era of Progress and Prosperity*, Public Affairs, New York, 2009, p. 45

[2] BVU (Beratergruppe Verkehr + Umwelt GmbH; translation: advisory group for traffic and the environment), DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V.; German Aerospace Center) and ISL (Institut für Seeverkehrswirtschaft und Logistik; Institute of Shipping Economics and Logistics), *Gleitende Mittelfristprognose für den Güter- und Personenverkehr. Mittelfristprognose Winter 2008/2009*, (German only; translation: *Sliding Middle Term Forecast for Freight and Passenger Traffic - Middle Term Forecast Winter 2008/2009*), Februar 2009; und Statistisches Bundesamt (Federal Statistical Office), press release No.135, 06 April 2009

[3] Julia King, Aston University, UK, *Ultra-Low Emission Vehicles: Energy-environment friendly by 2050?,* Conference *Energy 2050*, Stockholm, Sweden, 19/20 October 2009

[4] Nicholas Stern, see ref. [1], p.42 and *World Energy Outlook* 2008, Paris 2008

[5] International Energy Agency (IEA), study *CO_2 emissions from fuel combustion*, 2005

[6] Die Bundesregierung: *Fortschrittsbericht 2008 zur nationalen Nachhaltigkeitsstrategie* (The German Government: *Progress Report 2008 on the National Strategy for Sustainable Development*) http://www.bundesregierung.de/nn_774/Content/DE/Publikation/Bestellservice/2008-11-17-fortschrittsbericht-2008.html

[7] Werner Tillmetz, Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW; Centre for Solar Energy and Hydrogen Research) Baden-Württemberg, presentation *Batterien und Brennstoffzellen für die Elektromobilität,* (German only; translation: *Batteries and Fuel Cells for Electromobility*), Spring Meeting of the Working Group on Energy of the DPG (German Physical Society), Bad Honnef, 24 April 2009

[14] A few million in China; range 40-70 km

[8] Nationaler Entwicklungsplan Elektromobilität der Bundesregierung (National Electromobility Development Plan of the German Government), Berlin, August 2009, http://www.elektromobilitaet2008.de/

[9] www-toyota-prius.de

[10] Masatami Takimoto, Toyota Motor Corporation, *Toyota's Initiatives for Realizing Sustainable Mobility*, Presentation, 11 June 2008

[11] *CO_2-Ausstoß im Verkehrsmittelvergleich*, (German only; translation: *Comparison of CO_2 Emissions of Vehicles*) Deutsche Bahn AG (the German national railway company), Institut für Energie- u. Umweltforschung (ifeu; Institute for Energy and Environmental Research) und Öko-Institut (Institute for Applied Ecology)

[12] Hans-Jochen Luhmann, Wuppertal Institut (Wuppertal Institute for Climate, Environment and Energy), *100% Bahnstrom aus Erneuerbaren Energien in 2020! - Neue Option zur Abmilderung des Drucks auf das Biokraftstoffpotenzial* (German only; translation: *100% Electricity from Renewable Energies for Railway Transportation in 2020! – New Option for Mitigating the Pressure on the Potential of Bio Fuel*) GRV-Nachrichten Folge 85 (German only; translation: news by the GRV, Gesellschaft für Rationale Verkehrspolitik [Society for Rational Transportation Policies], vol. 85), December 2009, p.18

[13] Peter Westenberger, Deutsche Bahn AG (the German national railway company), *Wie klimafreundlich sind Bahn und Bus? Können Sie noch besser werden?* (German only; translation: *How Climate-Friendly are Railways/Trams and Busses? Can they be Improved?*), presentation at BUVKO (Bundesweiter Umwelt- und Verkehrskongress; translation: German-Wide Conference on the Environment and Traffic), Dresden, 22 March 2009

[14] Bernhard Wewers, Bundesarbeitsgemeinschaft Schienenpersonennahverkehr (BAG-SPNV; German governmental working group on short-distance rail traffic), *In Berlin alles beim Alten?* (German only; translation: *Has Nothing Changed in Berlin?*) Eisenbahn-Kurier (German only; translation: Railway Courier) 12-2009, p.3

[15] Ulrich Wagner, TU Munich, *Effizienzsteigerung durch Stromanwendung*, (German only; translation: *Improving Efficiency by Applying Electricity*), Fachtagung Stromversorgung des 21. Jahrhunderts (Topical Conference on Electricity Supply in the 21st Century), Munich, 29/30 April 2009

[16] Florian Finsterwalder, Head of Alternative Drives – Production Planning, Technology, Concepts, Daimler AG, Stuttgart, private communication

[17] Jörg Krug, E.ON Energie AG (E.ON energy company), Munich, *Elektromobilität und Energiewirtschaft – Zukunftsperspektiven für Energieversorger* (German only; translation: *Electromobility and Energy Economics – Future Perspectives for Energy Suppliers*), see ref. [15]

[18] M. Pehnt and U. Höpfner, Institut für Energie- u. Umweltforschung (ifeu; Institute for Energy and Environmental Research), Heidelberg, and F. Merten, Wuppertal-Institut für Klima, Umwelt, Energie (WIP; Wuppertal Institute for Climate, Environment and Energy), Wuppertal, *Elektromobilität und erneuerbare Energien* (German only; translation: *Electromobility and Renewable Energies*), November 2007

[19] Hanno Jelden, Volkswagen, *Energiespeicher für Elektrotraktion – Herausforderungen für Volkswagen* (German only; translation: *Energy Storage Units for Electric Traction – Challenges for Volkswagen*), Nationale Strategiekonferenz Elektromobilität (National Strategy Conference Electromobility), Berlin, 25/26 Novemeber 2008

[20] Alfred Oberholz, Evonik Industries, *Elektromobilität mit Li-Ionen Batterien aus Deutschland*, (German only; translation: *Electromobility by Li-ion Batteries from Germany*), see ref. [19]

[21] Joachim Maier, MPI für Festkörperforschung (Max Planck Institute for Solid State Research), Stuttgart, *Neue Wege der Batterieforschung* (German only; translation: *New Methods of Battery Research*), in *Die Zukunft der Energie*, (German only; translation: *The Future of Energy*) edited by P. Gruss and F. Schüth, C. H. Beck, Munich 2008, p. 282-294

[22] Jean-Marie Tarascon and M. Armand, *Issues and challenges facing rechargable lithium batteries*, Nature 414, 359-367 (2001)

[23] Jean-Marie Tarascon, Université de Picardie Jules Verne, *Batteries for Transportation Now and in the Future*, see ref. [3]

[24] FAZ (German newspaper "Frankfurter Allgemeine Zeitung") dated 24 November 2009: *Die Zukunft kommt – aber wie? – Toyota und seine Pläne für die nächsten 15 bis 20 Jahre* (German only; translation: *The Future's Coming – But in What Form? – Toyota and Its Plans for the next 15 to 20 Years*)

[25] Detlef Stolten, Institut für Energieforschung – Brennstoffzellen (IEF-3), FZ Jülich, (Institute for Energy Research – Fuel Cells [IEF-3], Research Centre Jülich), *Brennstoffzellen für mobile Anwendungen*, (German only; translation: *Fuel Cells for Mobile Application*), 74. Jahrestagung der DPG (74th Annual Conference of the German Physical Society), Bonn, 16 March 2010 http://www.uni-saarland.de/fak7/fze/AKE_Archiv/DPG2010-AKE_Bonn/Vortraege/DPG2010_AKE4.1_Stolten_Brennstoffzellen.pdf

Part II: Supply of electric energy

II.1 Fossil-based thermal power plants

1.1 The role of fossil-based power plants worldwide and in Europe/Germany

1.1–a Current status

Fossil energy sources form the backbone of energy supply (primary energy 82%, electricity generation 69%, see Tab.1) and will continue to do so over the next couple of decades (see Fig. 1). At the same time, the combustion of coal, mineral oil and natural gas is the main cause of climate-harmful CO_2 emissions. Measures aimed at reducing these emissions, such as increasing the efficiency of power plants (subchapter 1.2) and the separating out and storage of carbon dioxide (subchapter 1.3), therefore take highest priority.

Gross electricity production [%]			
	World	**EU-27**	**Germany**
Coal	**42**	**31**	**46.6**
Mineral oil	**6**	**3**	**1.5**
Natural gas	**21**	**22**	**11.9**
Nuclear energy	14	28	22.0
Renewable energies	18	15	14.2
Total electricity consumption [TWh]	**19,760**	**3,330**	**638**

Tab.1: Contribution of primary energy sources to gross electricity production in the world, the EU and Germany in 2007 [1]

While mineral oil plays the most important role in terms of primary energy, coal is used mainly for electricity generation (world: 42%; see Tab.1), followed by natural gas (world: 21%; see Tab.1). Coal provides high security of supply and its reserves and, above all, resources[1] will last for a comforting length of time, but it also produces the highest amount of CO_2 emissions per kWh of electricity. Apart from fossil energy sources, electricity supply in Europe and Germany is mainly based on nuclear energy; worldwide, the share of nuclear energy and renewable energies (currently mostly hydropower) is equally large.

The fact that fossil energy sources need to be imported for the most part is particularly serious for Germany and the EU (in 2006: Germany: 62%, EU-27: 55%), as is the currently increasing dependence on these imports[2].

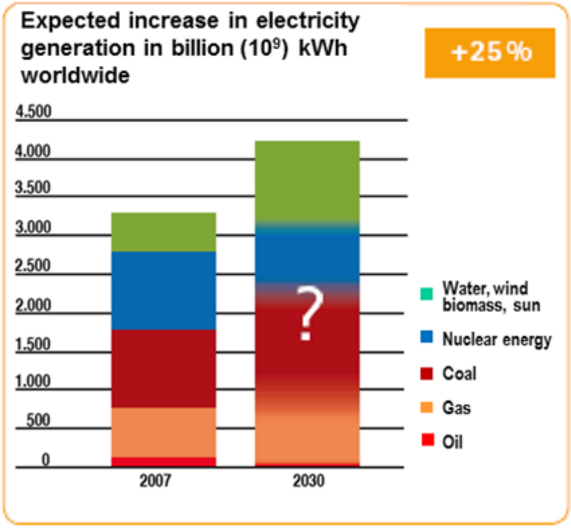
1.1–b Future demand

All of the future scenarios devoloped by the IEA [1] show that the worldwide energy demand will continue to increase over the next decades and the dominant role of fossil fuels will remain unaltered as well. Electricity consumption will increase similarly and actually even more rapidly due to the almost daily increasing amount of electric appliances and the desire for electrification in developing countries (see Part I of this study). As depicted in Fig. 1, the increase in electricity generation in the EU and worldwide by 2030 is estimated to be

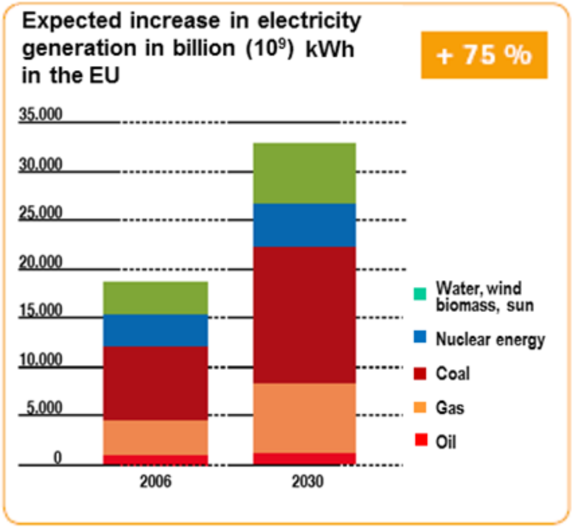
[1] The statistical reserves-to-production ratio, defined as the amount of a reserve in relation to mining, is 130 years for coal and 270 years for lignite; the corresponding resources will even last for several thousand years [2, 3].

[2] EU import rates for e.g. mineral oil were 60% in 2007 and an increase to 83% is expected by 2030 [1].

25% and 75% respectively (as compared to 2007 and 2006 respectively). Coal and natural gas remain the most important primary energy sources by far at together 55% and 65% respectively.



Source: Eurostat, IEA, calculations by the authors



Source: IEA

Fig. 1: Increase in primary energy consumption for electricity generation[3] in the EU and worldwide by 2030 [2]

The comparison of the estimated electricity demand with the existing power plant fleet and its age distribution[4] shows the need to build additional power plants in the next decades.

The demand for new power plants in Germany depends largely on the question of whether the political agreement for the phasing out of nuclear energy, reached in 2002, will stand. If it does, an additional 20,000 MW will need to be provided over the next 10-15 years as a consequence of the shutdown of nuclear power plants in addition to the age-related shutdown of fossil-based power plants. In this case, the German Energy Agency (Deutsche Energie-Agentur, dena) estimates a shortfall of 11,700 MW (assuming a decrease in electricity demand of 0.5% per year) and 15,800 MW (assuming a constant electricity demand)[5] between the peak load and the assured power plant capacity respectively for the year 2020. Depending on the scenario, extending the use of nuclear energy could delay by 10-15 years or even compensate entirely for this discrepancy. Statements by the German Federal Environment Agency (Umweltbundesamt) [5] and the Wuppertal Institute [6] disagree with the assessment by dena, however in doing so they take a noticeable reduction of electricity consumption (8% by 2020) and more optimistic scenarios for improving efficiency and the expansion of renewable energy sources as the basis of their analysis.

A corresponding analysis of the supply of electricity in the EU shows the need to build new power plants by 2020 generating about 300,000 MW (the sum of age-related replacements and additional electricity demand

---

[3] Conversion of amounts of electricity into power plant capacity: An installed power plant capacity of 114,000 MW is required in order to generate 1,000 TWh (= 1,000 billion kWh) of electricity (at an ideal availability of power plants of 100%; otherwise a larger capacity is needed).

[4] In Germany, the average useful life of fossil-based power plants is about 40 years for CCGT (combined-cycle gas turbine) power plants and 45 years for coal power plants.

[5] A recently updated version of the study by dena (Deutsche Energie-Agentur; German Energy Agency), *Kurzanalyse der Kraftwerksplanung in Deutschland bis 2020 (Aktualisierung), Berlin, Februar 2010* (German only; translation: *Short Analysis of Power Plant Planning in Germany up to 2020 [Update], Berlin, February 2010*) provides a slightly lower shortfall: 10,600 MW and 14,200 MW, assuming decreasing and constant demand for energy respectively.

assuming an increase in electricity demand of about 0.5% per year) [2]. By 2030, the WEO estimates the need for an additional 670,000 MW ("reference case" see [1]). The WEO predicts the need for an additional 3,000 GW worldwide by 2020 and 5,000 GW by 2030 (the figure for 2030 results fom the "reference case" and the "450ppm case" as well).

All these predictions are, besides estimates of future electricity demand, always based on estimates of the composition of the power plant fleet and accordingly use different figures with regard to the availability and assured power plant capacity of the examined types of power plants (fuelled by coal or natural gas, nuclear energy or regenerative energy sources).

The great demand for building new power plants on the one hand provides the chance to replace most of the old power plants with new ones using state-of-the-art technologies, on the other hand there is the danger that wrong building decisions may have long-lasting consequences and might make strategic changes towards a different, more economic or environmentally-friendly energy system more difficult at a later point.

Efforts to reduce CO_2 emissions from fossil-based power plants as completely and cost-effectively as possible[6], roughly speaking, follow two lines of thinking which are at very different stages of development and thus also have different time frames with regard to their large-scale application: One effort, based on "conventional" technology, is to improve the degree of efficiency of power plants and to replace coal with natural gas, the other is to separate out CO_2 during combustion and subsequently store it underground (carbon capture and storage, CCS). The required individual processes for the latter are well-known but their interplay still needs to be tested and developed to the level of large-scale industrial application. For this reason, CCS technology will only be available for industrial application in 10 to 15 years at the earliest, perhaps later than 2030[7]; in addition, people's acceptance of the final disposal of the required amounts of CO_2 must still be ensured.

1.2 CO_2 reduction through conventional technologies: Improving efficiency and replacing coal with gas

1.2–a Improving efficiency

While the efforts to increase efficiency were originally aimed at saving fuel costs, they nowadays focus on the reduction of carbon-dioxide and pollutant emissions.

Figure 2 depicts schematically the evolution of the efficiency and the average CO_2 emissions from hard coal power plants in the year 2000 to 2020 and beyond: The average degree of efficiency of power plants currently in operation is about 30% worldwide (for China/Russia only 22%), for the EU and Germany about 38%. New power plants built with currently available technologies already reach a degree of efficiency of 45% which is intended to be increased to more than 50% within in a few years by means of the 700°C technology[8].

[6] There are different state-sponsored programmes to help achieve this, e.g. the programme COORETEC by the German government and the initiative of the European Commission to build CCS pilot power plants [7].

[7] In an analysis by McKinsey [8], the reference case assumes an "early commercial period" shortly after 2020 and a "mature commercial phase" of about 100 projects in the EU at about the year 2030.

[8] These target values for the degree of efficiency of power plants regard installations in new condition and continuous operation at their optimum operation point near full load. In practice, these target values need to be adjusted according to aging, summer operation, partial load, and load follow operation, amongst other things. The calculations presented in chapter 1.4 therefore include a flat reduction by 2 percentage points.

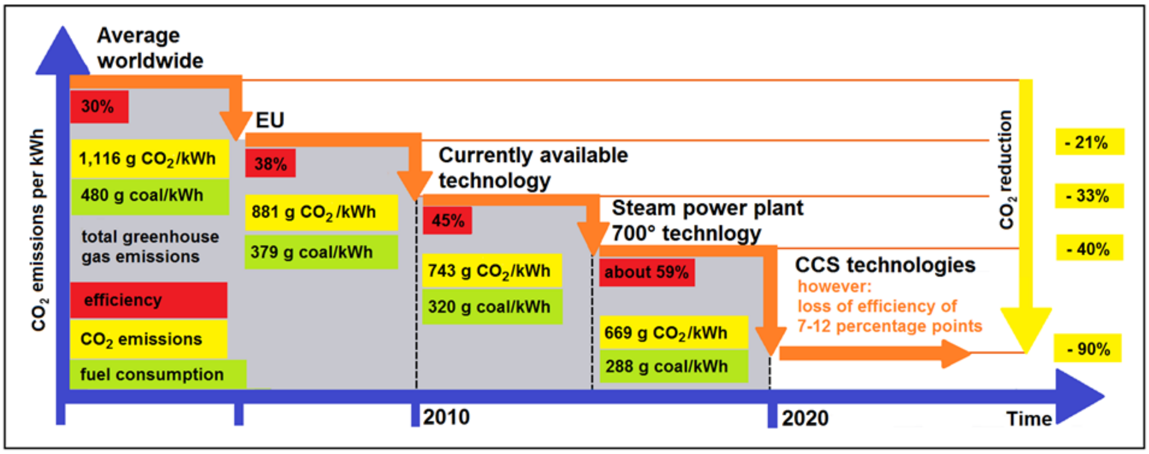


Fig. 2: Reducing CO_2-emissions from hard coal power plants by increasing their efficiency [2]

CO_2 emissions decrease according to the increase in efficiency from currently about 1120g CO_2/kWh (worldwide) and 880g CO_2/kWh (EU, Germany) to 740g CO_2/kWh for new power plants with current technology and to 670g CO_2/kWh with 700°C-technology later on. The latter figure corresponds to a reduction of CO_2 emissions by 40% compared to the present global average, however, it is still absolutely inacceptable in the long term. On the other hand, achieving increases in efficiency becomes more and more complex technologically. A breakthrough can only be achieved by means of CCS technology but at the expense of a significant loss of efficiency (7-12 percentage points) in conjunction with a corresponding increase in feedstock consumption as well as significant additional costs (see subchapter 1.3-c).

The further developments just mentioned focus, with regard to coal-fuelled steam power plants, on (cf. [9], chapter 3.3):
• the development of materials to master higher steam states, and
• the further optimisation of particular processes and components.
In the case of coal-fuelled steam power plants, the intended improvements should result in degrees of efficiency of about 53% by the year 2020; in the case of natural gas fuelled CCGT power plants 62% should be achievable.

1.2–b Replacing coal with natural gas

By replacing lignite with natural gas, the specific CO_2 emission can be halved, when replacing hard coal, the emission can be still reduced by a factor of 1.7. It is obvious, therefore, to replace coal fuelled power plants with natural gas fuelled CCGT power plants, which are, in addition, highly efficient (62%) and can be controlled easily (possibility to use them for load management).

Unfortunately, the advantages of natural gas have serious drawbacks, i.e. significantly higher costs[9] as well as the dependence on imports from politically unstable regions and the associated supply risks. This has led to a slower increase of electricity from natural gas in Germany than widely expected and so far it has fallen short of the estimates and demands made by the BMU [11] and UBA [12] in their scenarios of future energy supply[10].

---

[9] According to McKinsey [10], replacing hard coal with natural gas will incur avoidance costs of just under 30€/t CO_2 and replacing lignite just under 50€/t CO_2 in the year 2020.

[10] The pilot study 2008 ("Leitstudie 2008") [11] assumes that the share of natural gas of the installed power for fossil power plants will increase from 25% (20.4 GW) in 2005 to 41% (25.6GW) in 2020, which would require extending the contribution of natural gas by 73%. In reality, however, natural gas fuelled CCGT power plants are the minority of the envisaged fossil-based power plants in comparison to lignite or hard coal power plants [13].

1.3 Future development: Carbon capture and storage (CCS)

None of the discussed strategies for CO_2 avoidance put as much on the line economically and politically as the proposal to separate out the CO_2 generated during combustion in the power plant and subsequently store it underground. This process alone, if successful, offers the chance of further utilising the coal reserves available worldwide cost-efficiently without damaging the climate. Hence, it comes as no surprise that the energy supply industry as well as politicians are among the leading proponents of this technology. In its last assessment report (2007) the IPCC, too, included the concept of CCS in its portfolio of suggested mitigation activities to stabilise greenhouse gas concentration levels.

In recent years, many statements have been issued on CCS technology in general and on the question of how Germany shall proceed with regard to CCS [8, 14-22], and the evaluations contained in those statements present very different findings.

CCS technology can only be applied in case of large (>0.1Mt CO_2/year) localised point sources (about 80% are fossil-based power plants, the rest are iron and steel industry facilities, as well as chemical and concrete producing plants or refineries). These emitters produce about 60% of the amount of CO_2 generated by fossil fuels worldwide.

The CCS process consists of three steps: separation and capture, transport (by ship or via pipelines), and storage. Separation of CO_2 is the most expensive, long-term storage the most problematic step by far which might endanger the whole concept.

1.3–a CO_2 separation and compression: Processes, loss of efficiency

Three processes have emerged regarding the separation of CO_2 (cf. [9], chapter 9); their most important steps are depicted schematically in Fig. 3:

(1) post-combustion capture – chemical
(2) oxy-fuel process – combustion with O_2
(3) pre-combustion capture – gasification

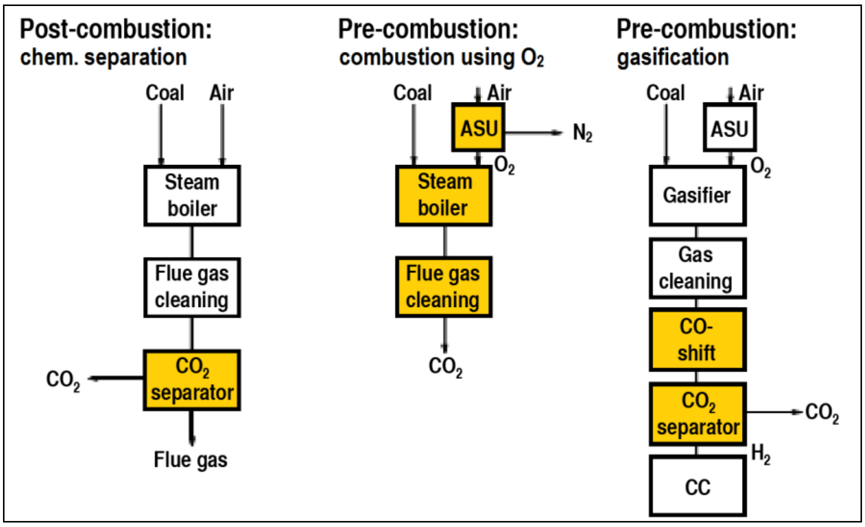


Fig. 3: Processes for CO_2 separation (schematically) [20]

(1) *Post-combustion*: CO_2 is extracted from the flue gas (mostly by chemical absorption) after coal combustion. The process relies on industrially proven technologies, but has the disadvantage of large volumetric flow rates (resulting in large facilities) and high energy consumption in order to regenerate the solvent. This results in a loss of efficiency of 10-14% (of this about 3.5% for the compression of CO_2). Conversely, it is suitable for retrofitting as it interferes only marginally with the power plant process.

(2) *Oxy-fuel process*: Coal is combusted with pure oxygen instead of air yielding significantly reduced amounts of flue gas. After purification, the flue gas consists essentially of a carbon-dioxide/water steam mix from which water steam can be condensed. As the production of pure oxygen (by air decomposition) requires much energy, the loss of efficiency in this case, too, is about 11.5% (again 3.5% due to compression).

(3) *Pre-combustion process*: In a first step, coal is converted into a synthesis gas of CO and H_2; subsequently, CO is converted to CO_2 and H_2 utilising water steam as an oxidant (exothermal CO shift reaction). After separation of CO_2 (chemical or physical absorption) the hydrogen-rich fuel gas can be used for largely emission-free electricity generation in a CCGT process (Integrated Gasification Combined Cycle (IGCC) power plant). The advantage of this process lies in the high gas pressure after the CO-shift reaction (which allows for economic use of physical absorbents) and low volumetric flow rates. The increased complexity of the system, however, is disadvantageous. Overall, this process is characterised by the lowest loss of efficiency (8-10 percentage points in total, 3 of which are lost due to compression) and reaches, at a total degree of efficiency of 42%, the efficiency level of current coal power plants.

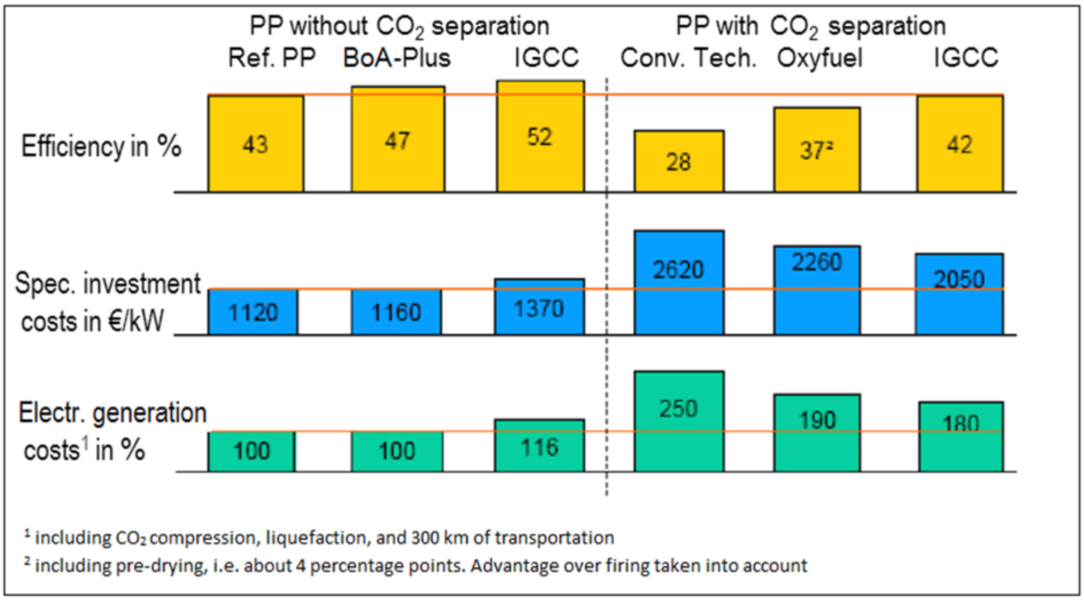


Fig. 4: CO_2 separation:
Comparison of processes with regard to degree of efficiency, specific investment costs and costs of electricity generation [20]

Figure 4 summarises these results by comparing the three CO_2 separation processes as well as three types of power plants without CO_2 separation in terms of their degree of efficiency, specific investment costs, and costs of electricity generation (the cost factor will be discussed again in subchapter 1.3-c). The superiority of gas fuelled IGCC power plants becomes apparent when examining their high degree of efficiency (52% without and 42% with CO_2-separation) already mentioned above and the low figure (28%) for CO_2 separation by means of the post-combustion process based on conventional technology. With regard to the costs it is apparent that CO_2 separation about doubles both the investment costs and those of electricity generation.

The separation and compression of CO_2 must be paid for by a loss of efficiency, $\Delta\eta$, of 11-14 %, for all CCS processes. This also means, however, that the generation of a certain amount of electricity with CO_2 separation (efficiency $\eta - \Delta\eta$) requires more coal than without CO_2-separation (efficiency η), that is at the ratio

$$\eta/(\eta - \Delta\eta).$$

If, for example, a $\Delta\eta$ of 12% is assumed, the fuel consumption of an "old" power plant with $\eta = 35\%$ increases by 52 %, while a "modern" power plant with $\eta = 46\%$ shows an increase of only 35%.

The loss of efficiency and the associated higher fuel consumption also cause all CCS processes to have a net CO_2 reduction coefficient, ε', which is slightly lower than the capture efficiency, ε, (typical figures in the range of 0.85-0.95). The net CO_2-reduction is

$$\varepsilon' = 1 - \eta\,(1-\varepsilon)/(\eta - \Delta\eta),$$

that is, for example, with $\varepsilon = 0.9$ and, as in the previous example, $\eta = 46\%$ and $\Delta\eta = 12\%$, it turns out to be $\varepsilon' = 0.865$, , i.e. a figure about 4 percentage points lower than that for ε. In this example, $(1- \varepsilon') = 13.5\%$ of the original CO_2 emissions still remain, even after employing CCS.

It must be noted, therefore, that even the application of CCS-technology does not lead to an entirely CO_2-free fossil-based power plant. About 15% of the original CO_2 emissions are not captured using current technology: residual emissions of about 124 and 107g CO_2 per kWh electricity remain for lignite and hard coal-fuelled power plants respectively [23].

For this reason, one of the main goals with regard to the further development of the CCS process is to reduce the loss of efficiency of currently 11-14% related to the CO_2 separation in the medium term (from about the year 2020 on) to perhaps 8-10% and in the long term (from the year 2030 on) to below 8% [8,16,21].

1.3–b Long-term storage of CO_2

There are, in principle, two options for the long-term storage of the vast amounts of accumulated CO_2: *Storage in the ocean* and *storage in suitable geological reservoirs*. CO_2 could be stored in liquid form (at depths up to about 3,000 m) in the oceans or undilutedly in a limited area on the ocean floor (CO_2 is heavier than water at depths greater than 3,000 m and sinks to the sea floor). In Europe, at least, oceanic storage has been ruled out for the time being as our knowledge of oceanic CO_2 storage is based exclusively on laboratory experiments and computer simulations, and furthermore, important questions have not been answered concerning the impact on marine fauna and flora as well as the time periods for which safe storage can be expected.

Table 2 summarises the estimates concerning geological CO_2 storage potentials [16] (see also [24]) the broad margin of the estimates reflecting the uncertainties in quantifying the assured storage potentials. The reserve-to-production ratio[11] amounts to a maximum of about 100 years with the exception of worldwide saline aquifers (with a maximum of 1,000 years). For this and other reasons, the German Advisory Council

[11] The reserve-to-production ratio refers to a fictitious feeding of all CO_2 emissions from the power plant sector of a particular region into this kind of deposit and thus represents a lower limit.

on Global Change (Wissenschaftlicher Beirat Globale Umwelt) has included the CCS concept in its 2003 policy paper [14] among its future scenarios only as a bridging technology.
Storing CO_2 in leak-proof geological formations, for instance in exploited gas and mineral oil fields, is state-of-the art technology (they are used as intermediate gas storage facilities, for example). The corresponding worldwide storage potentials are huge (see Tab. 2), although relatively low in Germany.

Deposit	**Global**		**Europe**		**Germany**	
	Capacitiy [Gt CO_2]	**Reserve-to-production-ratio [a]**	**Capacity [Gt CO_2]**	**Reserve-to-production-ratio [a]**	**Capacity [Gt CO_2]**	**Reserve-to-production ratio [a]**
Depleted gas fields	690	65	31 –163	21 – 110	3	8
Depleted oil fields / CO_2 EOR	120	11	4 –65	3 – 44	0,1	< 1
Deep saline aquifers	400 – 10,000	38 – 940	1 – 47	1 – 32	12 – 28	34 – 78
Undevelopable coal seams / ECBM	40	4	0 – 10	0 – 7	0.4 –1.7	< 2

Tab. 2: CO_2 storage capacities worldwide, in Europe and in Germany [16]

The extraction productivity of partially depleted mineral oil and gas fields can be increased by injecting CO_2 (so-called *enhanced oil/gas recovery*) so that a product price can be charged for CO_2.

The largest geological storage potential in Germany and worldwide can be found in deep salt-water bearing rock formations, so-called *aquifers*. Due to the geological conditions in Central Europe with regard to pressure and temperature as well as depth-dependent costs for the development of storage facilities, depths of about 900 to 1,000 m can be used for storage. The most comprehensive experience of CO_2 storage in aquifers was gained from the so-called Sleipner project off the coast of Norway where the energy company StatoilHydro has been injecting about one million tonnes of CO_2 a year since 1996 [25].

In principle, even unused *coal seams* are available for CO_2 storage. However, methane, formerly attached to the coal structure, is released during this process; for this reason, reservations are held about this type of CO_2 storage [16].

Furthermore, CO_2 can be bound as carbonates in mineral form or can be used in the field of chemical raw materials and energy sources (CO_2 recycling). However, only very low amounts of CO_2 (order of magnitude: one percent) can be used applying established industrial methods.

Besides the possibility of capturing and storing (CCS) the CO_2 continuously generated during combustion in fossil-based power plants, processes also have been discussed for some years which enable the binding of atmospheric CO_2 generated during earlier years of industrialisation (“new” carbon sinks; discussed in detail in [26]). Carbonisation of biomass (from waste or fast growing plants and algae) must be mentioned in this context in particular. In this process, the method of hydrothermal carbonisation (HTC)[12] plays an essential role, the underlying processes of which were investigated by Friedrich Bergius as early as 1913 [27] and have been taken up again by Markus Antonietti et al. in recent years and developed as a technologically attractive procedure [26, 28].

Another process for absorbing CO_2 from the atmosphere (by means of a solid sorbent) is described in [29].

[12] In this procedure the processes which led to the natural formation of lignite over a period of 50,000 to 50 million years are accelerated to take place within mere hours.

1.3–c CO_2 avoidance costs

The additional costs for a power plant with CO_2 separation are dominated by the higher investment costs. To this must be added the costs during operation which are related to the loss of efficiency.

Detailed model calculations show (e.g. in [16] and [20], cf. also Fig. 4) that CO_2 separation in coal power plants leads to almost a doubling of the electricity generation costs applying current technology and to an increase of about 50% for gas fuelled CCGT power plants.

The results of such cost comparisons can also be given as CO_2 avoidance costs for the various types of power plants (cf. [8, 13, 15, 16, 18, 20]): For the most optimistic estimate of the market introduction of CCS already by 2020 the CO_2 avoidance costs should lie in the range of 35 to close to 50 €/tCO_2 for coal power plants and in the range of 50 to 65 €/tCO_2 for gas-fuelled CCGT power plants. By 2030, costs could decrease to a range below 30 to slightly above 40 €/tCO_2 for coal power plants and to 45 to 60 €/tCO_2 for gas-fuelled CCGT power plants due to technological improvements and cost reductions.

1.3–d Window of opportunity for introducing CCS - public debate and legislation

Relatively high investment costs and long life times (in industrialised countries typically about 40 years) are important characteristics of current large-scale power plants and their associated energy infrastructure (e.g. grid of gas pipelines). Major modifications of the power plant fleets, such as the construction of new power plants with CO_2 separation, can only be realised in a narrow window of time – a window of opportunity. The decisive question, therefore, is when will the next window of opportunity open and whether one of the proposed methods of CO_2 separation will be ready for large-scale technical use (and at competitive costs, if possible) at that time. It is also important to know if old plants can be retrofitted and, if so, at what cost.

A detailed survey of the age-related necessary replacement of the German and European power plant fleets was presented in subchapter 1.1-b. In a detailed analysis the authors of [16] conclude that the construction of new power plants will reach its next peak around 2020 and subsequently decrease slowly (the scenarios presume the agreed phase-out of nuclear energy). The next significant reinvestment cycle would only occur around 2045. Thus the very near time frame around the year 2020 may be considered as the window of opportunity for the large-scale introduction of CCS technology. While such time-related predictions are characterised by large uncertainties, there are many indications that an enormous phase of constructing new power plants needs to take place in Germany around the year 2020 (the situation is similar in most European countries). However, it is more or less impossible for CCS technology to be tested und ready for large-scale use by that time (see footnote 7).

The contradiction between both time scales could be mitigated considerably if the expansion of renewable energy sources were to progress much faster, which, however, appears to be rather difficult as discussed at various points of this study. The possibilities and problems of nuclear energy, a fundamentally CO_2-lean alternative, will be discussed in detail in chapter II.2.

The temporal and strategic constraints (all-or-nothing situation) also explain why some do not want to allow for doubts to be raised at all about the technological and economic success of CCS technology and its availability around the year 2020 while others have fundamental doubts about the success – and in some cases even the necessity – of CCS. In any case, the great strategic importance of this technology does not only justify but also virtually enforces that every effort be made to find answers to those many open questions as soon and as comprehensively as possible.

In Germany, all four of the major electricity supply companies have realised the importance of CCS technology and accordingly are pressing ahead with the construction of pilot power plants (preliminary stage and prerequisite for a large-scale demonstration power plant). In September 2008, Vattenfall started operating a 30 MW CCS pilot power plant based on the oxy-fuel process located at Schwarze Pumpe in the Lusatia region of Brandenburg. The separated CO_2 is to be stored in a saline aquifer near Ketzin/Brandenburg[13]. In the autumn of 2009, E.ON and Siemens started operating a pilot plant for CO_2 separation at the coal power plant Staudinger in Großkrotzenburg/Hesse. RWE intends to build an IGCC-CCS coal power plant capable of flue gas scrubbing in Hürth near Cologne while the separated CO_2 is to be transported via a 500km long pipeline to the designated deposit in Schleswig-Holstein. In all three cases vehement protests by the affected population took place which led to a draft law on separation, transportation and storage of CO_2, worked out by the German government in 2009, not being passed at the designated time.

The problem of the CCS strategy, therefore, is not so much CO_2 separation, which will most likely be possible on a large scale – albeit at higher costs and much later than desired – but rather safe CO_2 underground storage for thousands of years[14]. The reactions by the population show similar fears in this regard as with regard to the disposal of nuclear waste. Another point of criticism is the fact that the limited storage space in Germany is also needed for utilisation of deep geothermal energy and storage of natural gas, hydrogen, and compressed air [22].

1.4 Estimation of the achievable reduction of CO_2 emissions in relation to electricity generation by the year 2030

We will now examine how Germany's fossil-based power plant fleet has been developing since 1990 and what kind of prediction can be made for the year 2030. The tables regarding gross electricity generation [32] and the use of various fossil energy sources for electricity generation published by the Working Group on Energy Balances (Arbeitsgemeinschaft Energiebilanzen) [33] form the data base of recent years. The figures 330, 400, 190 and 300 g CO_2/kWh for hard coal, lignite, natural gas, and mineral oil respectively are used for the amounts of CO_2 released during combustion[15]. In addition, a constant gross electricity generation from fossil fuels of 376 billion kWh[16] is assumed in order to estimate the specific CO_2 reductions achievable by 2030.

Table 3 (column 2 and 3) and Fig. 5 show the development of the power plant fleet from 1992[17] to 2008. The average specific CO_2 emission (per kWh) of all fossil-fuelled power plants decreased by 13.8% within this time period. This is due to an improvement of the average degree of efficiency of power plants[18] from 38.1%

---

[13] In addition, Vattenfall plans to start building a demonstration facility in 2010 which is intended to go into service between 2013 and 2015 [30].

[14] There are no proven scientific findings yet about whether CO_2 can be stored for long periods without leakage. A positive sign is that CO_2 has been stored in the Norwegian gas field Sleipner since 1996 – without leakage [25]. The Federal Environment Agency (Umweltbundesamt) is of the opinion that a leakage rate of 0.1% is to be generally classified as unobjectionable [31].

[15] According to the 2005 study of the German Physical Society [9].

[16] This corresponds to the figure for the year 2003 which was used in the DPG study and is assumed to remain constant until 2020. This figure has fluctuated between 370 and 383 billion kWh in the last years (2004-2008) but has dropped to 345 billion kWh due to the economic downturn in 2009.

[17] The years 1990 and 1991 are not suited for comparison as the closing down of out-of-date lignite power plants in the course of German reunification was not yet completed.

[18] With regard to power plant efficiency it must be noted that the increasing contribution of renewable energies to the process of electricity generation in recent years has led to an increased controlling power demand on fossil-based power plants and, as a consequence, to a decrease in their overall efficiency.

to 42.3% in addition to an increase in the share of natural gas in electricity production from 10% to 23%. On an absolute scale, the reduction of CO_2 emissions is only 7% for this time period as electricity generation has simultaneously increased by 8%.

			Gas share doubled (46%)		CCS technology for ¼ of PP	
	1992	2008	2030		2030	
			$^4/_5$ ordinary PP	$^1/_5$ gas-CCGT	$^3/_4$ ordinary PP	$^1/_4$ PP with CCS
Hard coal						
efficiency, %	39.7	41.1	44		44	(36.7)[1]
share of electricity, %	41.4	33.6	22.3		25.2	8.4
CO_2-em.fact., gCO_2/kWh	830	803	750		750	107
Lignite						
efficiency, %	35,6	38.2	42		42	(37.5)[1]
share of electricity, %	45.1	40.6	29.3		30.5	10.1
CO_2-em.fact., gCO_2/kWh	1,124	1,047	952		952	124
Natural gas						
efficiency, %	42.7	55.4	49	58,5	56	(51)[1]
share of electricity, %	9.6	23.4	23.4	22,6	17.6	5.8
CO_2-em.fact., gCO_2/kWh	445	343	388	325	388	67[2]
Mineral oil						
efficiency, %	42.4	38.1	46		46	(39)[1]
share of electricity, %	3.8	2.5	2.5		1.9	0.6
CO_2-em.fact., gCO_2/kWh	707	787	652		652	82[2]
Sum of fossil energy carriers						
share of electricity, %	100	100	77	23	75	25
weighted CO_2-em.fact., gCO_2/kWh	920.6	793.9	553.3	+73,4	559.4	+26.0
			626.7		585.4	

[1]not used in calculations [2]interpolated from various data

Tab. 3: Development of the specific CO_2 emissions from the fossil-based power plant fleet from 1992 to 2008 as well as estimates for the year 2030 of possible improvements compared to the trend by increasing the share of gas or the partial use of CCS technology. Our own calculations.

An evaluation of the data 1992-2008 (see Fig. 5) shows a decrease in the specific CO_2 emissions from the fossil-based power plant fleet by 0.876% per year. Extrapolating this figure to 2030, the specific CO_2 emission from the fossil-based power plant fleet is 661g CO_2/kWh (trend figure) for 2030 which equates to a decrease by 29% compared with the figures of 1990. The trend figure presumes the power plant fleet to continue to develop in the way it has done since 1992, meaning that the fuel mix will retain its current composition, except for a moderate increase of the natural gas share, and that the efficiencies of the various types of power plants can be further improved at the current growth rate.

Next, we will examine to what extent the trend figure for the year 2030 can be further improved if either the fuel mixture is changed in favour of natural gas even beyond the share suggested by the trend (cf. subchapter 1.2-b) or some of the newly-built power plants are equipped with CCS technology (cf. chapter 1.3).

For the first case, we doubled the electricity share from natural gas from 23% today to 46% (a very ambitious assumption) and presumed that this increase occurs at the equal expense of the use of hard coal and lignite (corresponding to current experience) (Tab. 3, columns 4 and 5). We further assumed that the additional share of natural gas is produced by new and modern CCGT power plants which will go into service in the years 2010-2030 and will replace the oldest hard coal and lignite power plants (which went into service between 1990 and 2000).

We then have two classes of natural gas power plants: The "old" half (i.e. the natural gas power plants of the reference case) which have an average degree of efficiency of 49% (average of the operating time period from 1990 to 2030) and a "new" half consisting of additional CCGT power plants with an average degree of efficiency of 58.5% (average of the operating time period from 2010 to 2030)[19,20]. For the remaining power plants fuelled by hard coal, lignite, and mineral oil, we assumed average degrees of efficiencies of 44, 42, and 46% respectively (averages over the operating time period from 2010 to 2030, in case of mineral oil power plants from 1990 to 2030, although, with 2.5%, their contribution to electricity generation is negligible).

Based on these assumptions, in 2030, the specific CO_2 emission of the fossil-based power plant fleet will have been reduced to 627 g/kWh (gas share doubled), which is 5% lower than the trend figure.

For the second case we examined to what extent the CO_2 emissions from the power plant fleet might be reduced by the year 2030 if CCS technology were available on a large scale from 2020 onwards and the older quarter of the respective power plants (the fuel mix is assumed to remain unchanged compared to the year 2008) were replaced by new power plants using CCS technology[21] (Tab. 3, column 7). The CO_2 emission factors were again calculated on the basis of the figures provided in [23] (using averages of the years 2020 to 2030). For the remaining power plants without CCS technology (Tab. 3, column 6) the degrees of efficiency presented in Tab. 3, column 4 were used.

In this case, the specific CO_2 emission from the fossil-based power plant fleet would only be 585 g/kWh (1/4 CCS-technology) in 2030, 11.5% less than the trend would suggest. The more power plants retrofitted with CCS-technology the more this figure can be reduced, of course. The specific CO_2 emission of the fossil-based power plant fleet could be reduced to 425 g/kWh (1/2 CCS-technology), which equates to a reduction of 55% compared to 1990, if half of all power plants were equipped with CCS technology. The real breakthrough, however, will have been achieved only when virtually all power plants are equipped with CCS technology. The entire fossil-based power plant fleet, then, would emit only 107 gCO_2/kWh (full CCS-technology) [23], equating to 11% of the figure from 1990.

An examination of the *life cycle analysis* of CO_2 emissions from various types of electricity generating power plants as carried out by the Paul-Scherrer-Institute [34] for example, reveals that the CO_2 emission figure for coal power plants using CCS technology roughly corresponds to that for photo-voltaic, but is larger by a factor of 5 to 10 compared with the figures from wind, hydro and nuclear energy. On the other hand, it is more than a factor of 6 below most future state-of-the art hard coal power plants (cf. Fig. 2).

[19] These considerations are based on a mean life time of 40 years for the power plants and assume that "old" power plants are being replaced continuously by "new" ones.

[20] The figures for the degree of efficiency of the various types of power plants for the years 2010 to 2030 were taken from [23] – they were adjusted by the mentioned reduction of two percentage points due to non-optimal operation – and for the years 1990 to 2008 from the corresponding data provided by the Arbeitsgemeinschaft Energiebilanzen (Working Group on Energy Balances) [32, 33].

[21] For the sake of simplicity we only considered new power plants using CCS technology. In principle, power plants can be retrofitted, of course. However, it is very expensive and requires the necessary space to have been set aside. Only 11 of the 30 coal power plants currently planned or under construction are considered "capture ready", however [13].

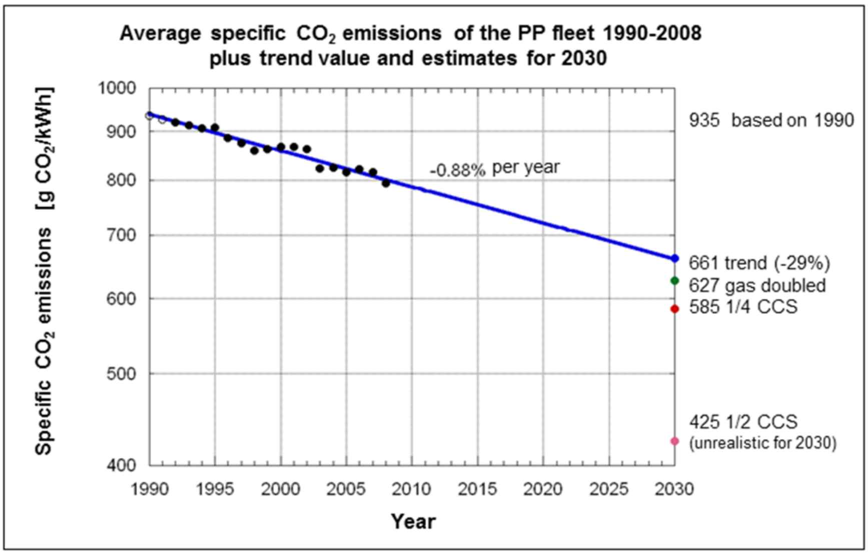


Fig. 5: Development of the specific CO_2 emissions from the German fossil-fuelled power plant fleet between 1990 and 2008 as well as "trend value" and two estimates for 2030 ("gas share doubled" and "partial utilisation of CCS technology")

These results have been summarised in Fig. 5. It is obvious that without the use of CCS technology the CO_2 emissions from the fossil power plant fleet can be reduced only to the extent suggested by the trend (about -30% compared to 1990) – and even that requires huge efforts. Only if at least half of the coal power plants are equipped with CCS technology – which will not be the case prior to 2030 – can reductions reach 50% or more. As electricity generation by fossil-based power plants provides, at 35%, the largest share of the overall emission of carbon dioxide (accordingly, the development over time of both factors is very similar during the time period 1990 – 2008), this result also provides an indication of the order of magnitude for realistic reductions of the overall CO_2 emissions in Germany.

1.5 Summary and outlook

Coal will remain the cheapest and most readily accessible primary energy source for many decades and thus will continue to play a central role in the worldwide energy supply. By 2030, the CO_2 emissions related to the combustion of fossils might be reduced by improving the efficiency of power plants by 15%, by a considerable expansion of the gas share by up to 25%, in Germany (and similarly in other industrialised countries). The reduction of the entire amount of CO_2 emissions by at least 80% demanded for the middle of the century can, however, only be achieved by means of carbon dioxide separation and storage (CCS). Therefore, the timely development of such processes, including tests of their large-scale suitability and economic competitiveness in demonstration facilities, is of fundamental importance. At present it cannot be predicted whether these efforts will be successful. In parallel to the technological development the necessary legislation needs to be enacted and the people be convinced of the advantages and necessity of the CCS process by a broad information campaign.

Difficulties may arise from the fact that CCS technology will most likely not be available on an industrial scale before 2030, whereas the window of opportunity for the construction of new power plants will open around 2020. Retrofitting conventional power plants, which would need to be built in the meantime, is only possible in a limited way and at relatively high costs. In Germany, the situation could be eased substantially if the expansion of suitable renewable energy systems could be accelerated further. Otherwise, extending the operating time of existing nuclear power plants remains the only solution.

Notes and references:

[1] International Energy Agency (IEA), World Energy Outlook 2009, Paris 2009

[2] Association of power plant operating companies, VGB PowerTech e.V., brochure *Zahlen und Fakten zur Stromerzeugung 2009/10* (German only; translation: *Figures for and Facts about Electricity Generation 2009/10*)

[3] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR; Federal Institute for Geosciences and Natural Resources), *Energierohstoffe 2009: Reserven, Ressourcen, Verfügbarkeiten* (German only; translation: *Energy Resources 2009: Reserves, Resources, Availability*)

[4] Deutsche Energie-Agentur (dena; German Energy Agency), *Kurzanalyse der Kraftwerks- und Netzplanung in Deutschland bis 2020 (mit Ausblick bis 2030),* (German only; translation: *Short Analysis of Power Plant and Grid Planning in Germany up to 2020 [Including an Outlook on 2030]*), Berlin, March 2008

[5] Umweltbundesamt (UBA; German Federal Environment Agency), Berlin, March 2008

[6] F. Matthes and H.-J. Ziesing, *Die Entwicklung des deutschen Kraftwerksparks und die aktuelle Debatte um die künftige Strombedarfsdeckung*, (German only; translation: *The Development of the German Power Plant Fleet and the Current Debate on Future Energy Supply*), Berlin, April 2008

[7] European Commission, *Supporting Early Demonstration of Sustainable Power Generation from Fossile Fuels*, COM(2008) 13 final, Brussels, 2008

[8] McKinsey&Company, *Carbon capture and storage: assessing the economics*, September 2008

[9] Deutsche Physikalische Gesellschaft (DPG; German Physical Society), Arbeitskreis Energie (AKE; Working Group on Energy), study: *Klimaschutz und Energieversorgung in Deutschland 1990-2020 / Climate Protection and Energy Supply in Germany 1990 – 2020*, September 2005

[10] McKinsey&Company, study commissioned by "BDI Initiativ – Wirtschaft für Klimaschutz" ("BDI Initiative – Industries for Climate Protection"), *Kosten und Potenziale der Vermeidung von Treibhausgasemissionen in Deutschland,* (German only; translation: *Costs and Potential for Avoiding Greenhouse Gas Emissions in Germany*), September 2007, p.34

[11] J. Nitsch, *Ausbaustrategie Erneuerbare Energien* (German only; translation: Expansion Strategy Renewable Energies), pilot study 2008, commissioned by the BMU (Bundenministerium für Umwelt, Naturschutz und Reaktorsicherheit; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Berlin, October 2008; and: *Leitszenario 2009*, study commissioned by the BMU (Bundenministerium für Umwelt, Naturschutz und Reaktorsicherheit; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Berlin, August 2009

[12] Umweltbundesamt (UBA, German Federal Environment Agency), Climate Change 05/07: *Klimaschutz in Deutschland: 40%-Senkung der CO_2-Emissionen bis 2020 gegenüber 1990*, (German only; translation*: Climate Protection in Germany: 40% Reduction of CO_2 Emission by 2020 as Compared to 1990*), May 2007

[13] A. Löschel, *Die Zukunft der Kohle in der Stromerzeugung in Deutschland – Eine umweltökonomische Betrachtung der öffentlichen Diskussion*, (German only; translation: *The Future of Coal With Regard to Electricity Generation in Germany – An Environmental Economic View of the Public Debate*), Energiepolitik 1/2009 (Energy Policies 1/2009), Arbeitskreis Energiepolitik (Working Group on Energy Policies), Friedrich-Ebert-Stiftung (Friedrich Ebert Foundation)

[14] Wissenschaftlicher Beirat Globale Umweltveränderung (WBGU; German Advisory Council on Global Change): *Welt im Wandel – Energiewende zur Nachhaltigkeit / Serving Global Change Policies*, 2003

[15] IPCC Special Report on Carbon Dioxide Capture and Storage. WG III of IPCC, 2005

[16] FZ Jülich (Research Center Jülich), *Zukünftige Energieversorgung unter den Randbedingungen einer großtechnischen CO_2-Abscheidung und Speicherung*, (German only; translation: *Future Energy Supply within the Framework of Large-Scale Carbon Capture and Storage*), final report, April 2006

[17] M. Fischedick, et al., *Strukturell-ökonomisch-ökologisch-ökonomischer Vergleich Regenerativer Energietechnologien mit Carbon Capture and Storage*, (German only; translation: Structural-Economic, Ecological-Economic Comparison of Regenerative Energy Technologies with Carbon Capture and Storage), Wuppertal Inst. f. Klima, Umwelt, Energie (Wuppertal Institute for Climate, Environment and Energy) in co-operation with DLR (Deutsches Zentrum für Luft- und Raumfahrt; German Aerospace Center), ZSW (Zukunftsorientierte Wärme Systeme; translation: Future-Oriented Heating Systems) and PIK (Potsdam-Institut für Klimafolgenforschung; Potsdam Institute for Climate Impact Research) supported by the BMU (Bundenministerium für Umwelt, Naturschutz und Reaktorsicherheit; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), 2007

[18] Bundesverband der deutschen Industrie (BDI; Federation of German Industry) and McKinsey, *Kosten und Potenziale der Vermeidung von Treibhausgasen in Deutschland*, (German only; translation: *Costs and Potential for Avoiding Greenhouse Gas Emissions in Germany*), September 2007

[19] GreenPeace, *Falsche Hoffnung: Warum CO_2-Abscheidung und -Lagerung das Klima nicht retten werden* (German only; translation: *False Hope: Why Carbon Capture and Storage Won't Save the Climate*), May 2008

[20] H. Spliethoff, Technische Universität Munich, presentation *Moderne Kohlekraftwerke – Effizienzsteigerung und CO_2-Abscheidung* (German only; translation: *Modern Coal-Fuelled Power Plants – Improving Efficiency and Separation of CO_2*) at a meeting of the Arbeitskreis Energie (AKE; Working Group on Energy) of the DPG (Deutsche Physikalische Gesellschaft; German Physical Society) on 23 April 2009

[21] P. Markewitz et. al., Institut für Energieforschung – Systemforschung und Technologische Entwicklung (IEF-STE; Institute for Energy Research – System Analysis and Technology Evaluation), FZ Jülich (Research Center Jülich), presentation at the topical conference *Energietechnologien 2050 – Kraftwerkstechnologien*, (German only; translation: *Energy Technologies 2050 – Power Plant Technologies*), Berlin on 26 May 2009

[22] Sachverständigenrat für Umweltfragen (SRU; The German Advisory Council on the Environment), *Abscheidung, Transport u. Speicherung von Kohlendioxid – Der Gesetzentwurf der Bundesregierung*, (German only; translation: *Separation, Transportation and Storage of Carbon Dioxide – Bill by the German Government*), April 2009

[23] A. Voß, Institut für Energiewirtschaft und Rationelle Energieanwendung (IER; Institute for Energy Economics and Rational Energty Application), University of Stuttgart, reference data set for power plants (as of 31 July 2009), private communication

[24] F. May et al., Bundesanstalt für Geowissenschaften und Rohstoffe (BGR; Federal Institute for Geosciences and Natural Resources), *Assessing the European potenzial for geological storage of CO_2 – the GESTCO Project*, Proc. of GHGT 7, Vancouver, 2004

[25] SpiegelOnline (German online newspaper), 3 December 2006, *CO_2-Speicher im Meer – Teures Seegrab für den Klimakiller*, (German only; translation: *CO_2 Storage in the Ocean – An Expensive Burial at Sea for the Climate Killer*) http://www.spiegel.de/wissenschaft/natur/0,1518,451308,00.html

[26] M. Antonietti and G. Gleixner, *Biomasse-Nutzung für globale Zyklen: Energieerzeugung oder Kohlenstoffspeicherung*, (German only; translation*: Biomass Utilisation for Global Cycles: Energy Generation and Carbon Storage*)
in *Die Zukunft der Energie* (German only; translation: *The Future of Energy)*, edited by P. Gruss and F. Schüth, Verlag C. H. Beck, Munich 2008, p. 212-222

[27] F. Bergius and H. Specht, *Die Anwendung hoher Drücke bei chemischen Vorgängen*, (German only; translation: *Applying High Pressures during Chemical Processes*), Halle 1913

[28] M. M. Titirici, A. Thomas and M. Antonietti, *Back in the black: hydrothermal carbonization of plant material as an efficient chemical process to treat the CO_2 problem?*, New Journal of Chemistry 31, 787-789 (2007)

[29] K.S. Lackner, *Capture of carbon dioxide from ambient air*,
in: European Physics Journal (EPJ) Special Topics 176, 93-106 (2009)

[30] T. Hatakka, Chairman of Vattenfal Europa, in German newspaper Der Tagesspiegel, 14 September 2009

[31] Umweltbundesamt (UBA; German Federal Environment Agency), *Technische Abscheidung und Speicherung von CO_2 – nur eine Übergangslösung* (German only; translation: *Technical Separation and Storage of CO2 – Just a Temporary Solution*), position paper oft he UBA, Berlin, 2006

[32] Arbeitsgemeinschaft Energiebilanzen (AGEB; Working Group on Energy Balances) 2009:
Bruttostromerzeugung in Deutschland von 1990 bis 2009 nach Energieträgern (German only; translation: *Gross Electricity Generation in Germany from 1990 to 2009 by Energy Carriers*) (as of 18 December 2009)

[33] see ref. [32]: *Einsatz von Energieträgern zur Stromerzeugung in Deutschland 1990-2008* (German only; translation: Application of Energy Carriers for Electricity Generation in Germany 1990-2008) (as of 29 September 2009)

[34] Paul Scherrer Institut (PSI; Paul Scherrer Institute), *CO_2-Emissionen aus dem nuklearen Kreislauf* (German only; translation: *CO_2 Emissions from the Nuclear Cycle*), PSI-Fachinfos zu Energiefragen (German only; translation: PSI topical information on energy issues), 06 March 2007

II.2 Nuclear power plants *

The use of nuclear energy has been controversially discussed in Germany. Even the Atomic Energy Act, newly formulated in 2002 and aimed at phasing out nuclear energy, could not bring an end to the controversy, especially as a reassessment of nuclear energy has been taking place in other countries and intergovernmental institutions in recent years.

Discussions about a reassessment of nuclear energy have been going in Germany as well – however, decisions can only be made by the political institutions. This chapter aims to contribute to the current discussion about the future of nuclear energy in Germany on a factual basis.

2.1 International situation

2.1–a Nuclear energy within the current energy supply system

The peaceful use of nuclear energy began with the first British and Soviet pilot nuclear power plants in the mid-1950s, i.e. more than half a century ago; the first nuclear power plant in the US was connected to the grid in 1960, the first nuclear power plant in Germany in 1961. Today, nuclear (fission) energy is used to generate electricity in 31 countries, in some cases also utilising cogeneration of heat and power, i.e. combined with the supply of process steam for industrial purposes or heat for district heating. Two thirds of the world's population live in countries which have their own nuclear power plants. As of 1 October 2009, 436 nuclear power plants were in operation worldwide with a total installed net-power of 370.2 Gigawatts (GW) [1]. In 2008, their net production, i.e. without internal consumption, was 2,628 terawatt hours (TWh)[1] per year and thus covered 14% of the world's electricity consumption (Tab. 1).

Continent	Number	Net power, GW	Net electricity generation, 2008, TWh
Europe	195	169.6	1,179.4
of which: EU-27	*144*	*131.5*	*915.4*
Switzerland	*5*	*3.2*	*27.6*
Russia	*31*	*2.,7*	*152.1*
Ukraine	*15*	*13.1*	*84.3*
America	128	117.3	927.8
Africa	2	1.8	13.3
Asia	111	81.5	507.5
World	**436**	**370.2**	**2,628.0**

Tab. 1: Nuclear power plants in operation, by continent, as of 1st October 2009

* Note added in translation: The events in the nuclear power plants in Fukushima/Japan (March 2011), which were triggered by the extreme earthquake and subsequent tsunami, have strongly impacted on the public perception and political positions regarding nuclear power in many parts of the world. The German Government plans a phasing out of nuclear energy which shall be completed by around 2022. In this situation, the German Physical Society (DPG) urges not to neglect the important objectives in climate protection and based on renewable energies in particular also including non-fluctuating sources, in order to guarantee a stable and secure energy therefore calls for enhancing the efforts in improving the efficient and effective use of energy and in establishing an energy supply basis as needed for society.

[1] 1 TWh = 1 billion kWh

Electricity from nuclear energy has a firm place within global electricity supply comparable to the importance of hydropower. Europe is even ahead of the US with regard to using nuclear energy in terms of the number and installed power of nuclear power plants as well as the electricity generation per year. In Germany, 17 nuclear power plants contributed 23% to overall electricity generation in 2008, providing about half of the base load. Germany ranked sixth – after the US, France, Japan, Russia, and South Korea – with regard to nuclear electricity generation providing 141.5 TWh.

2.1.–b Construction of new nuclear power plants

As of 1st October 2009, 53 nuclear power plants with a total power of 48 GW were under construction in 14 countries; 10 of these projects were begun in 2008, another 10 in 2009 (4 of which are revived nuclear projects). Of these 53 projects, 17 are located in Europe (1 in Finland and France each, 2 in Bulgaria, Slovakia, and Ukraine each, 9 in Russia). More than 100 further projects in various countries were at the – more or less definite – planning stage.

Major expansion programmes are under way in Russia, China, India, and South Korea, and in development in the US and the UK. In addition, a large number of countries intend to start introducing nuclear energy. Of these, Poland, Egypt, Jordan, the United Arab Emirates, Turkey, and Indonesia have the most concrete plans. Italy has decided to return to nuclear energy, is currently rebuilding the necessary infrastructure and intends to start construction in the next few years. The Swedish government intends to authorise the replacement of older nuclear power plants with new ones. Further construction projects are planned, for instance, in Finland, France, Lithuania, the Netherlands, Slovakia, the Czech Republic, Switzerland, and Hungary.

2.1.–c Current contribution of nuclear power to climate protection

Nuclear power plants do not emit greenhouse gases while in operation. However, for a factual comparison with other methods of electricity generation a life cycle analysis is necessary which encompasses all stages from construction and operation to dismantling the power plant and disposing of its waste.

A recent study [2] by the Paul-Scherrer-Institute in Würenlingen/Switzerland reports a CO_2 equivalent of 8-11 g/kWh for nuclear energy in Switzerland, as compared to 4 g/kWh for hydropower and 36 g/kWh for wind power. Similar studies by various German and international institutions assign a range of 5 to 33 g CO_2-equivalent/kWh [3] to nuclear energy. In other words, nuclear energy is virtually CO_2-free, as is wind power and hydropower, when compared to the emissions of about 800 g/kWh from modern hard coal-fuelled power plants and about 1,000 g/kWh from lignite-fuelled power plants (Fig. 1).

If the amount of 141.5 TWh in Germany in 2008 had not been generated by nuclear power plants but by all the other power plants generating Germany's energy mix, CO_2 emissions from the electricity generating sector would have been larger by more than 100 million tonnes or by 30%. Nuclear energy thus contributes substantially to climate protection today.

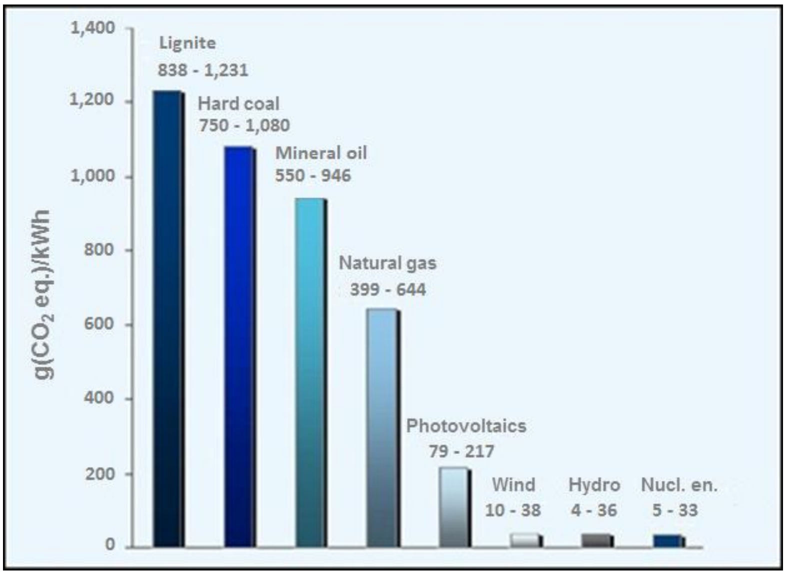


Fig. 1: Life cycle analysis of CO_2 emissions for different types of power plants (according to various sources)

2.1.–d Reassessment of nuclear energy in terms of energy policies with the goal of security of supply and climate protection

The construction of nuclear power plants had come to a halt in most industrial countries of the western word even before the Chernobyl accident in April 1986. The most important reasons for this were saturation tendencies in the electricity market, growth of consumption falling short of estimates, oversupply of inexpensive fossil fuels and the decreasing public acceptance of nuclear energy.

As a consequence of the Chernobyl accident the acceptance of nuclear energy hit rock bottom. The reason behind this accident was an unnecessary and irresponsible experiment which was carried out, after important safety systems had been deactivated, in a reactor type lacking inherent safety. In subsequent years, on German initiative, the G7 countries started an aid programme for the improvement of safety of Russian-built reactors in Central and Eastern Europe and for the shutdown of particularly unsafe ones.

Beginning around the year 2000, a reassessment of nuclear energy with regard to security of supply and climate protection was taking place in Western Europe. In 2002, Finland acted as the trailblazer, deciding to build a new nuclear power plant. On 10 January 2007, the European Commission passed its Green Paper *An Energy Policy for Europe* [4] and a new *Illustrative Nuclear Programme* which both contain a clear plea for nuclear energy. The European Commission describes nuclear energy as one of the largest sources of virtually CO_2-free energy in Europe and considers nuclear energy not only as a bridging technology but as a component of a low-carbon energy system by the year 2050. The Commission therefore not only supports the life time extension of existing nuclear power plants but also the construction of new ones as well as the development of new types of nuclear power plants, the so-called Generation IV reactors.

In November 2007, the European Commission drew up the *European Strategic Energy Technologies Plan* (SET plan) in order to implement its energy and climate protection policy and elaborated on the necessary measures in its “Technology Roadmap” in October 2009. Both documents, which also focus in detail on the forced adoption of renewable energies, on energy saving and CCS, regard nuclear energy as an essential element for attaining a low-CO_2 energy future.

The International Panel on Climate Change (IPCC) acknowledged nuclear energy as a technology for mitigating climate change in its Fourth Assessment Report. The contribution of the Working Group III "Mitigation of Climate Change" [5], published in May 2007, expects not only an absolute increase of nuclear energy use by 2030 but also a percental increase of electricity generation from 14% today to 18%.

2.1–e Scenarios for the future supply contribution of nuclear energy

The reassessment of nuclear energy is also reflected in the scenarios developed by institutions active in the field of energy supply. As late as in the year 2000, the International Energy Agency (IEA), Paris, estimated in its annual publication *World Energy Outlook* that both nuclear power installed worldwide and nuclear electricity generation would be in decline from 2000 onwards. Today the future of nuclear energy is assessed differently.

In its reference scenario reflecting present energy policies, the IEA, in its November 2009 issue of *World Energy Outlook 2009* [6], estimated an increase from 370 to 475 GW between 2007 and 2030 for installed nuclear power. The IEA report also examined a scenario meeting the IPCC's requirements of stabilising the atmospheric CO_2 concentration at 450 ppm. In order to reach this goal, only CO_2-free power plants should be granted building permission, i.e. power plants based on regenerative energy sources, coal-fired power plants with CCS technology, and nuclear power plants. This scenario indicates for 2030 nuclear power of 748 GW and a doubling of nuclear electricity generation against 2007.

The *Nuclear Energy Agency* (NEA) of the OECD presents two scenarios in the very first issue of Nuclear Energy Outlook [7] published in October 2008 covering the time period until 2050; both scenarios comply with the IPCC's climate protection goals but are based on different assumptions with regard to the increase in renewable energies and CCS technology. The "high scenario" assumes an increase in installed nuclear power up to about 600 GW by 2030 and up to 1,400 GW by 2050; in 2050 nuclear electricity generation is 3.8 times higher than in the reference year 2006 and covers 22% of the electricity demand that has increased by a factor of 2.5. The "low scenario" assumes that a slight extension of nuclear energy to 580 GW by 2050 will suffice to meet the climate protection targets. In their scenarios, both institutions, the IEA and the OECD/NEA, assign an important role to nuclear energy as part of a system of sustainable energy supply conforming to the requirements of climate protection.

2.1–f Consolidated reactor technology, restoring capacities of manufacturers

During the last five decades, nuclear technology has continuously consolidated; water cooled reactors have proven to be dependable and cost-effective workhorses. Current nuclear power plants and those being built are dominated by light-water reactors (pressurised and boiling water reactors, PWR and BWR respectively) and heavy-water reactors (D_2O-PWR), the latter of which are being used in a small number of countries.

This concentration on water-cooled reactors facilitates the international exchange of experiences and the harmonisation and further development of safety requirements.

Due to the decline in construction of nuclear power plants since the late-1980s, manufacturers of reactors and the supply industry have adjusted their capacities in the engineering sector as well as on the production side. Reductions in staff were accompanied by a loss of expertise. For about five years, manufacturers have been expanding their capacities again as a consequence of the apparent revitalisation of the construction of nuclear power plants in OECD countries and the dynamic nuclear expansion in China. Improving job chances in the field of nuclear energy has led to an increase in the number of students choosing nuclear technology as their major or minor subject and to an expansion of courses taught in various countries. However, these processes require time and effort, and rebuilding nuclear competence also includes learning the hard way as, for example, the delays and cost increases of the Finnish Olkiluoto-3 project are demonstrating.

The expansion of the capacities of the nuclear fuel cycle also requires long lead times. This is true in particular for uranium mining: the development of a new mine requires at least ten years. However, in light of market prospects, the expansion of uranium production began several years ago in all major supplying countries.

2.1–g Technological trends and further developments

In the next two decades, there will hardly be any alternatives to light water reactors. With nearly all of the test and prototype reactors of the early days with power up to 300 MW, i.e. Generation I reactors, having been shut down, almost all of the reactors in nuclear power plants operating today are so-called Generation II reactors. They have been proven to be both reliable and economic, and the operating companies and regulatory authorities estimate that they can be operated safely even beyond the originally intended lifespan of 40 years. In the US, more than half of all 104 nuclear power plants have already had their operating license extended to 60 years.

Since the 1990s, seven international nuclear power plant manufacturers have developed ten Generation III reactor types within the established reactor lines, which are now on the market worldwide. Several of these reactor types have passed the licensing process in at least one country and are already in operation or under construction; others are being assessed by the “standard design certification process“ which, in this form, exists only in the US.

In accordance with the requirements of the regulatory authorities and electricity providers, these new developments largely share the main objectives, i.e. further enhanced safety and reduction of radioactive waste on the one hand and improved cost-effectiveness on the other.

2.1–h Generation IV reactors

Since the turn of the century, the leading industrialised countries have been focusing increasingly on the long-term future of nuclear energy in their research and development. International cooperation is the characterising feature of this new development rather than the essentially separate national programmes existing so far. Four initiatives need to be mentioned:

- Generation IV International Forum (GIF)
- International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)
- Global Nuclear Energy Partnership (GNEP)
- Strategic Energy Technologies Plan of the EU.

These initiatives, which are interconnected in various ways, are aimed first and foremost at:

- advancing the use of nuclear energy in additional countries without increasing the risk of proliferation of nuclear weapons or terrorism;

- multiplying the energy yield of uranium (by up to a factor of about 50) by developing Generation IV reactors and applying nuclear energy increasingly beyond the mere generation of electricity, for instance in combined heat and power, desalination of sea water, and hydrogen production; as well as

- ensuring the sustainability of the use of nuclear energy. The closed fuel cycle, an essential feature of Generation IV, is one of the prerequisites for drastically increasing the energy gain from uranium and for the reduction of the amount and longevity of radioactive waste through partitioning and transmutation of long-lived actinides.

2.2 Status quo in Germany

2.2–a State of affairs in Germany in view of the nuclear-phaseout policy

Abiding by the provisions of the Coalition Agreement of 20th October 1998, the then-German government initiated the gradual phaseout of the peaceful utilisation of nuclear energy. To this end, the 10th Amendment to the Atomic Energy Act of 27th April 2002 limits the lifespan of existing nuclear power plants to 32 years and sets a maximum permitted residual electricity amount for each individual plant according to its age; once this amount has been generated the operating license expires. The lifespan limitation was the result of negotiations with the energy supply companies despite divergent opinions on the use of nuclear power. In return, the German government guaranteed in the Agreement the politically undisturbed operation of the power plants for the remainder of their lifespan. In addition, the German government acknowledged that the companies' "nuclear power plants and other nuclear installations were being operated by international standards on a high safety level"[8].

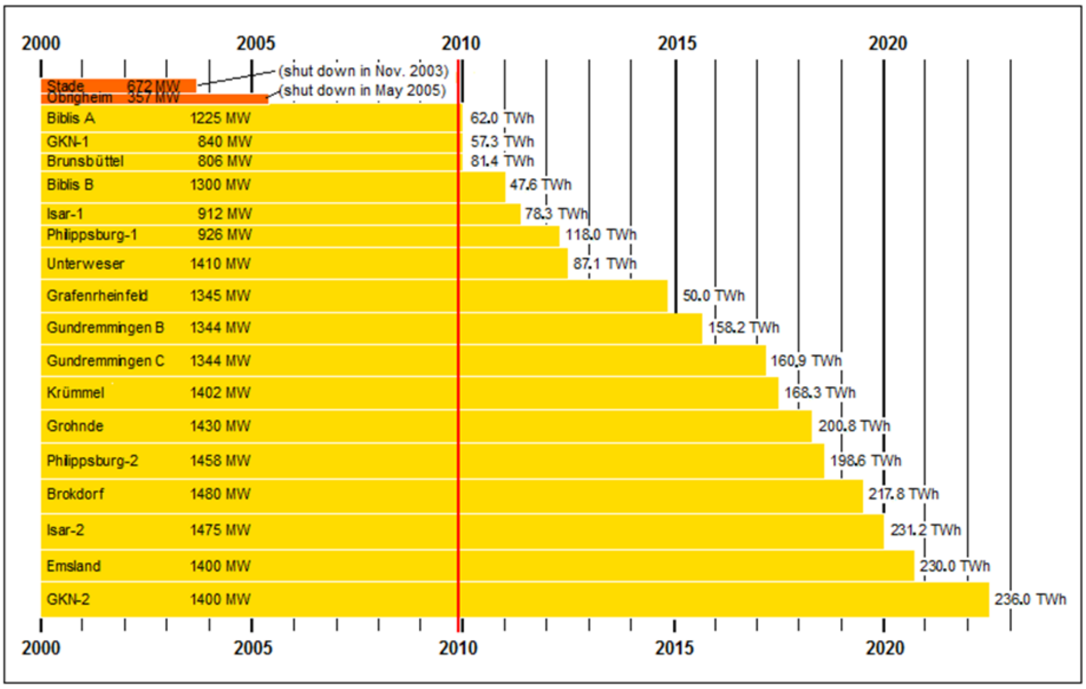


Fig. 2: Shutdown plan in accordance with the Amendment of 2002 to the Atomic Energy Act, as of February 2009 (source: EnBW)

By autumn 2009, only the relatively small nuclear power plants Stade (672 MW, November 2003) and Obrigheim (340 MW, May 2005) had been shut down in Germany as a result of the phase-out policy. During the 2009-2013 legislative period, an additional 7 out of the remaining 17 nuclear power plants are going to use up their permitted residual amount of electricity and thus are to lose their operating license. According to this road map, the last nuclear power plants will have to be shut down shortly after 2020 (see Fig. 2). The new German government consisting of the CDU, CSU and FDP parties is looking into extending the lifespans of Germany's nuclear power plants in compliance with strict German and international safety standards.

2.2–b The role of nuclear energy in a future electricity supply system
with a large share of fluctuating electricity?

The share of temporal fluctuating electricity is going to increase with the expansion of regenerative electricity generation. Storage capacity – mainly pumped-storage power plants – however is very limited. Balancing electricity demand and supply, therefore, must happen via flexibly controllable power plants. Contrary to popular belief, German nuclear power plants are, by design, not limited to operating with constant power load. Rather, they are designed to cope with fast changes of load [9] in the upper load range (between 50 and 100% of their nominal power). This applies to both pressurised water and boiling water reactors. As Fig. 3 shows, a nuclear power plant can increase or decrease its power by 20% of its nominal power on demand within two minutes and, within ten minutes, from full load to half load and vice versa. Thus, nuclear power plants are more flexible than conventional steam power plants [10]. Reasons for that are good controllability of the nuclear fission process and the control technology designed for just this particular purpose. Effects such as fatigue of materials are taken into account in the layout design and are subjected to continuous monitoring as part of the statutory ageing management.

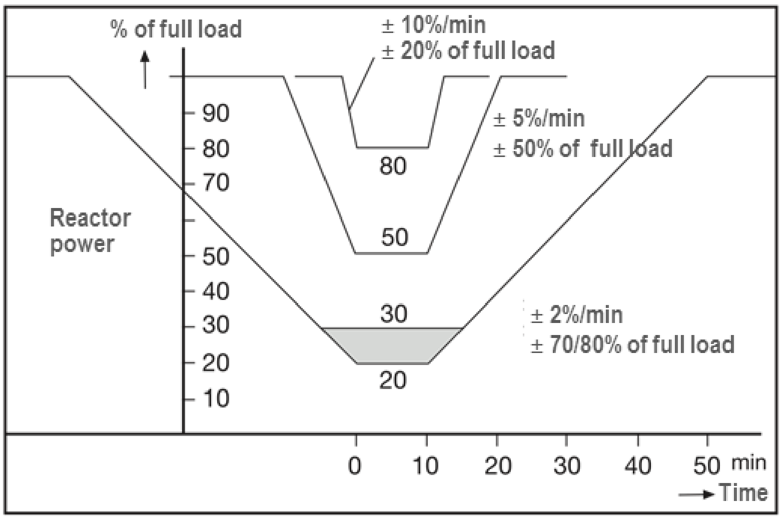


Fig. 3: Load change capability of German pressurised water reactors

The capability of several German nuclear power plants to counter balance fluctuating electricity from wind power is being utilised increasingly in order to stabilise the grid. Due to the large number of nuclear power plants in France – nearly 80% of the electricity generated is nuclear – it is common practice to run some nuclear power plants in load following mode.

In this regard, a possible lifespan extension of nuclear power plants does not hamper the further expansion of renewable energies.

2.2–c Further utilisation of existing nuclear power plants – from a safety viewpoint

All German nuclear power plants held an indefinite operating license – as is the case in France, Sweden and Switzerland, for instance (the US and other countries grant 40-year operating licenses which can be extended to 60 years) – up until the Atomic Energy Act was amended in 2002. With regard to cost-effective generation of electricity and climate protection, the lifespan extension of German nuclear power plants may be an option worth considering given the analysis above. Now the question must be asked whether this is justifiable from a reactor safety viewpoint.

The safety level of German nuclear power plants can be demonstrated by an analysis of notifiable events (termed “special occurrences” until 1990). Since 1991, notifiable events are classified – in addition to the German classification into the groups normal (“normal”), urgent (“eilt”), and immediately (“sofort”) – in accordance with the international classification scale with regard to their safety-related significance. During the entire 18-year period of applying the seven-level International Nuclear and Radiological Event Scale (INES scale), there has not been a single “serious incident” (INES level 3). Of the 2529 events reported between 1991 and 2007, 74 were classified as “anomaly” (INES level 1), i.e. deviation from the normal operation of the power plant, and three events as “incidents” (INES level 2), defined as a limited failure in graduated safety measures. All other notifiable events were “Below Scale / Level 0” on the INES scale, i.e. they were without (or only very minor) safety significance.

The emission of radioactive material via exhaust air and waste water amounts regularily to only a mere fraction of the authorised values.

Every ten years, each nuclear power plant is subject to a periodic safety review (Periodische Sicherheitsüberprüfung, PSÜ), supplementing continuous regulatory monitoring of the power plants and identifying necessary safety improvements, if any, with regard to the latest state of technology and science. Similarly, a systematic ageing management was introduced in order to register and monitor ageing processes.

Possible measures in order to guarantee long-term reactor safety are, amongst other things:

- operational safety review by an international team of experts (OSART-mission of the IAEA, as carried out at the nuclear power plants Phillipsburg and Neckarwestheim in recent years),
- screening of the plants with regard to modernisation needs, for example in the control technology sector with its distinct technological progress,
- reviewing the intervals for in-service inspections of welding seams with regard to material fatigue.

Applying these measures, longer lifespans of existing nuclear power plants are justifiable from a reactor safety viewpoint.

2.2–d Construction of new nuclear power plants in Germany

The construction of new nuclear power plants is currently not under consideration. According to the Coalition Agreement, the current German government will adhere to the ban on building new power plants. Nevertheless, it is important for Germany to continue to participate in nuclear research and international scientific exchange – regardless of whether the political institutions may be interested in the new build option at a later date.

2.2–e Key factors for the acceptance of continued utilisation of nuclear energy

The utilisation of nuclear energy requires its acceptance by the majority of the population and thus is subject to political decisions[2]. The latter are not the subject of this study which merely supplies scientific and factual information.

2.3 Fuel supply and waste management

2.3–a Range of uranium reserves

Uranium is a heavy metal. It is found everywhere in the Earth's crust and is about as common as tin and tungsten. Fears that the uranium reserves are dwindling are partially based on a misconception of the geological term "reserves". Geologists define the term "reserves" not as the totality of the deposits of a mineral feedstock on our planet but merely as that part of the known deposits which can be economically exploited with current mining methods, in other words, which can be profitably mined at current market prices. If prices rise due to shortage, a further part of the known deposits becomes "reserves".

Furthermore, there is more uranium than geologists have explored and located so far. A thorough prospection took place only between 1970 and 1985. Uranium prospection essentially came to a halt as the construction of nuclear power plants fell short of expectations and the oversupply beat down uranium prices. In addition, uranium from the military sector of countries with atomic weapons has become available in the course of nuclear disarmament and is being introduced to the market little by little.

The known assured and estimated additional uranium deposits – with extraction costs below 130 US$/kg uranium – amount to 5.4 million tonnes or 82 times the current annual demand. Considering the current increased market price of above 150 US$/kg uranium, the totality is to be classified as "reserves" in the geological sense.

Apart from the resources in "conventional" deposits, large amounts of uranium can be found in phosphates and sea water. The amount of uranium in phosphates is estimated to be between 7 to 22 million tonnes with extraction costs of 40-115 US$/kg. In the future, even these unconventional uranium deposits may become economically relevant. As the costs of uranium currently amount to just 5% of the costs of nuclear electricity generation, it will be possible to utilise uranium deposits with much higher extraction costs without nuclear energy becoming uneconomical.

The largest uranium reserves are found in Australia, Kazakhstan, the US, Canada, and South Africa. Due to the geographical distribution of the resources security of supply is high.

Less than 1% of the atoms of mined uranium is actually fissioned in current reactors. The yield can be increased by up to 20% by reprocessing the spent fuel elements and recycling the plutonium produced as

---

[2] In this regard, politicians need to consider and assess the following issues: (1) Prioritising is needed of climate protection, energy costs, and utilisation risks of nuclear energy. (2) The major share of the additional profit margin of nuclear power plant operating companies should be invested in energy research and/or directly benefit electricity consumers. (3) The people must be able to realise that no increased risks are expected from the extended utilisation of nuclear power plants. (4) An appropriate solution must be found for the final disposal of highly radioactive waste. (5) The international community of states must do all in their power to prevent the proliferation of nuclear weapons.

well as the unused uranium. There is also a huge technological potential for the development of uranium-saving reactors including fast breeders which provide a multiple of the energy yield per kilogramme of natural uranium (see subchapter 2.1-h, Generation IV reactors). By all possible standards, the range of uranium resources thus is virtually unlimited.

In its most recent study of energy resources [12] the German Federal Institute for Geosciences and Natural Resources (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) concludes: “Even in the future, the use of nuclear energy will not be limited by the availablity of nuclear fuel” (“Die Nutzung von Kernenergie ist auch in Zukunft nicht durch die Verfügbarkeit der Kernbrennstoffe limitiert”).

2.3–b Global status of disposal of radioactive waste

In Germany, two waste categories are used to classify final disposal:

- waste with negligible heat generation (i.e. low-level radioactive waste and the major part of intermediate-level radioactive waste),
- heat-generating waste (i.e. high-level waste from reprocessing spent fuel elements or spent fuel elements themselves as well as some intermediate-level radioactive waste such as parts of fuel assembly structure).

Sites for final disposal of waste with negligible heat generation are available in many countries such as Finland, France, the UK, Japan, Sweden, Spain, and the US. They are all located near to the surface or closely below the surface. Another approach is the “Waste Isolation Pilot Plant – WIPP” near the town of Carlsbad in the state of New Mexico, USA. Since March 1999, the trans-uranium (TRU) waste from the US nuclear weapons production has been placed into this newly constructed final disposal site, a deep geological salt formation. Germany and Switzerland have opted for deep geological storage even for waste with negligible heat generation.

The installation of a repository in the former iron ore mine Konrad for low-level and intermediate-level waste – in Germany also defined as waste with negligible heat generation – was approved in Germany in 2002 at the end of a licensing procedure which had lasted 20 years. Construction began five years later once all lawsuits had been dismissed by the highest German court. The repository is set to commence operation in 2014. 90% of all radioactive waste (volume wise) of this waste category is to be placed into this repository, amounting to just 1% of the total radioactivity of the waste to be disposed of in Germany.

All countries follow the concept of final disposal of heat-generating waste in deep geological formations in order to ensure long-term isolation of radioactive material from the biosphere. The spectrum of suitable rock formations is broad and depends, naturally, on the geology of a country. Promising rocks are granite, rock salt, and clay. As yet, no repository for this waste category is in operation anywhere in the world; however, in several countries projects are underway and have already reached an advanced state of planning:

- In Finland, the selected site of Olkiluoto was approved by the Finnish government and parliament. At present, the underground laboratory Onkalo is being set up at a depth of 420 m at the location of the future repository where the physical and chemical properties of the rock (granite) of the final repository, needed for the licensing procedure in 2012, are being examined. Beginning in 2015, the repository and the associated facility for conditioning of spent fuel elements will be constructed. Storing at a depth of 500 m is due to commence in 2020.

- Final disposal in granite is also planned by Sweden. From several communities which applied to host the repository, the site Forsmark in the Östhammar community was selected after exploration wells were drilled in two different locations in June 2009. The licensing application was due in 2010. After licensing, expected in 2013, the repository will be constructed by 2023.

- France has opted for final disposal in a 150 million years old clay formation. At present, an underground laboratory is being operated at the site Bure (Lorraine). The licensing application is due by 2015 and construction of the repository by 2025. The exact site for the repository in the region of Bure has yet to be decided.

- The Swiss government accepted the proof of disposal ("Entsorgungsnachweis") of high-level radioactive waste in 2006, based on the exploration of opalinus clay near Benken in the Zürcher Weinland. The National Cooperative for the Disposal of Radioactive Waste ("Nationale Genossenschaft für die Lagerung radioaktiver Abfälle – Nagra"), responsible for the disposal, suggested seven sites in 2008, amongst them six in opalinus clay, one in marlstone. The "Plan for Deep Geological Repositories" ("Sachplan geologische Tiefenlager") intends to start operating the repository for high-level waste in 2040.

- In the US on the other hand the situation is not clear. The site Yucca Mountain, Nevada – in the vicinity of the former atomic weapons test site – was approved by the US government and Congress, after more than twenty years of exploration, in 2002 despite objections by the Governor of Nevada. In 2008, the Department of Energy submitted the application documents to the licensing authority. However, Barack Obama already opposed Yucca Mountain during his presidential campaign. An alternative strategy is not in sight and thus, for the time being, intermediate storage of spent fuel elements continues. President Obama appointed a new commission at the end of January 2010 to propose a new strategy. The commission is entrusted with including reprocessing and recycling in their considerations.

- In accordance with the Atomic Energy Act, the responsibility for establishing and operating final repositories in Germany rests with the German government which conferred responsibility on the German Federal Office of Radiation Protection (Bundesamt für Strahlenschutz). The costs are to be borne by the waste producers, i.e. the nuclear power plant companies, industry, research centres, hospitals etc., that is by commercial or public institutions. The political institutions have been favouring the final disposal in salt-rock formations since the end of the 1960s. Since 1979 the salt dome Gorleben has been under exploration, with an interim moratorium since 2000. The experimental repository Asse II was established in order to provide experience, but its geology poses a problem. It is to be shut down in the future.

The laws of physics play only a minor role in the assessment of repositories as compared to geological or political (acceptance by the population) factors which is why this study cannot provide further details for political decision-making. The problem of final disposal, however, ranks first in the public and political debate of nuclear energy in Germany. As the final disposal of high-level radioactive waste has not yet been solved and the worries and fears of the population have not been dispelled sufficiently, the problem of final disposal has become one of the deciding factors for a large part of the population for opposing the use of nuclear energy. A satisfactory and safe solution to the problem of final disposal must be found soon, regardless of the lifespan of German nuclear power plants.

2.4 Summary and outlook

A political reassessment of nuclear energy has been taking place worldwide. Apart from its cost-effectiveness and security of supply, the climate compatibility of nuclear energy is a strong positive argument in the assessment reports by the IAEA, IEA, OECD/NEA and the IPCC. These institutions expect an increasing contribution of nuclear energy to the electricity supply in industrialised and some threshold countries over the next decades.

The European Physical Society also comes to the conclusion in its November 2007 position paper Energy for the Future – The Nuclear Option [13] that "nuclear power can and should make an important contribution to a portfolio of electricity sources".

In Germany, too, nuclear energy could also continue to do its part in achieving ambitious climate protection goals.

A central issue in this regard is public acceptance which can be improved by embedding nuclear energy in a coherent concept of energy and climate policy and by swiftly establishing a repository for high-level radioactive waste.

Notes and references:

[1] All data according to IAEA, Power Reactors Information System (PRIS)
http://www.iaea.org/programmes/a2/

[2] Paul Scherrer Institut (PSI; Paul Scherrer Institute): *CO_2-Emissionen aus dem nuklearen Kreislauf* (*CO_2 Emissions from the Nuclear Cycle*), PSI-Fachinfos zu Energiefragen (PSI topical information on energy issues), 06 March 2007
http://www.psi.ch/medien/Medienmitteilungen/Beitrag_zur_CH_Energiedebatte/Beitrag_zur_CH_Energiedebatte.pdf

[3] *Kernenergie: Klimaschutz vom Anfang bis zum Ende* (German only; translation: *Nuclear Energy: Climate Protection from Beginning to End*), press release by the Deutsches Atomforum (German Atomic Forum), 21 March 2007
http://www.kernenergie.de/kernenergie/Presse/Pressemitteilungen/items/2007-03-21_kernenergie_klimaschutz.php

[4] European Commission Green Paper *An Energy Policy for Europe*, 10 January 2007
http://europa.eu/legislation_summaries/energy/european_energy_policy/l27067_de.htm

[5] *Klimaänderung 2007: Verminderung des Klimawandels / Climate Change 2007: Mitigation of Climate Change*. Contribution of the Working Group III to the Fourth Assessment Report of the IPCC (p.13)
http://www.ipcc.ch/pdf/reports-nonUN-translations/deutch/IPCC2007-WG3.pdf

[6] International Energy Agency (IEA), *World Energy Outlook 2009*, Paris 2009
http://www.worldenergyoutlook.org/2009.asp

[7] OECD/NEA: *Nuclear Energy Outlook 2008*, *Kernaussagen und Zusammenfassung* (German only; translation: *Central Issues and Summary*), Paris 2008
http://www.oecd.org/dataoecd/45/48/41504144.pdf

[8] Agreement between the German government and energy supply companies, 14 June 2009
http://www.bmu.de/files/pdfs/allgemein/application/pdf/atomkonsens.pdf

[9] W. Aleite, *Lastfolgefähigkeiten von Kernkraftwerken mit Druckwasserreaktoren* (German only; translation: *Load Follow Capabilities of Nuclear Power Plants with Pressurised Water Reactors*), VGB (association of power plant operating companies) conference Kraftwerke (Power Plants), 1985

[10] M. Hundt et al.: *Verträglichkeit von erneuerbaren Energien und Kernenergie im Erzeugungsverbund* (German only; translation: *Compatibility of Renewable Energies and Nuclear Energy within the Generating Network*), Stuttgart, October 2009
http://www.ier.uni-stuttgart.de/publikationen/pb_pdf/Hundt_EEKE_Langfassung.pdf

[11] Bundesamt für Strahlenschutz (The Federal Office for Radiation Protection): *Systematik der internationalen Bewertungsskala (INES) (System of the International Nuclear Events Scale [INES])*
http://www.bfs.de/de/kerntechnik/ereignisse/ines.html

[12] *Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen 2007*. (German only; translation*: Reserves, Resources and Availability of Energy Feedstocks 2007*), short study by the BGR (Bundesanstalt für Geowissenschaften und Rohstoffe; Federal Institute for Geosciences and Natural Resources), November 2008
http://www.bgr.bund.de/cln_101/nn_322848/DE/Themen/Energie/Downloads/Energiestudie__Kurzf__2007.html?__nnn=true

[13] *Energy for the Future – The Nuclear Option*. Position paper by the European Physical Society, 2007
http://www.eps.org/about-us/position-papers

II.3 Combined heat and power generation and systems comparison

The simultaneous generation of heat and electricity serves to facilitate a more effective use of fuel. The technology of combined heat and power generation (CHP) is used in a multitude of applications, on the one hand for industrial own generation, on the other for public supply of electricity and district heating, both of which are of almost equal importance in Germany and Europe[1,2].

Electricity generation coupled with heat generation represents only a small, continuously increasing share of the total electricity generation so far; it amounted to 11% in Germany in 2000 and 12% in 2007; European figures are similar[3].

CHP has already been mentioned in chapter I.2 as, in theory, an elegant and effective way of utilising the exergy of fuels to a larger extent than during mere combustion. There are a variety of applications, facilities and modes of operation for the cogeneration of heat and electricity [1, 2, 3]. The exact gain in fuel utilisation depends on the mode of operation of each facility which, moreover, changes all the time. Averaged over all plants and all used fuels the overall fuel utilisation of CHP in Germany in 2002 was estimated to be 79% (EU-25: 70%)[4].

Impressed by their high percentage of fuel utilisation, the German government has set a target figure intending to double the share of electricity from CHP plants to 25% by 2020. Supporting measures were codified by law (CHP law, KWK-Gesetz 2009 [7]).

In view of the fact that a high percentage of fuel utilisation is not an appropriate feature of quality when assessing the amount of fuel being saved using a given user profile (cf. subchapter 3.2-c, final paragraph), this chapter examines which technology of producing heat and power will be the optimum in the future. In this regard, technological developments need to be considered which are able to change the general perception of CHP for some important applications, namely:

- achieving much better efficiencies for pure (separate) electricity generation,
- the nowadays common condensing technology which allows for better efficiencies for pure (separate) heat generation by firing installations,
- as well as the advent of well-functioning and efficient heat pumps whose reliability can most certainly be improved in the future.

For this reason, this chapter examines the actual or supposed advantages of combined production in comparison with separate generation of electricity and heat. Of course, a comprehensive overview cannot be given here; instead, particularly important individual examples will be selected. The emphasis is placed on CHP plants for buildings using natural gas as a fuel, the expansion of which is particularly favoured by the German government in view of the intended doubling of the CHP share. It will be demonstrated that the expansion of CHP in the future is not always the ideal way of utilising the fuel most efficiently or economically – contrary to what is frequently assumed.

---

[1] In 2002, the electricity generated by CHP plants in the EU-25 amounted to 163.1 TWh (public) + 136.1 TWh (industrial), and in Germany to 33.3 TWh (public) + 22.9 TWh (industrial) [4].

[2] A comprehensive overview of combined heat and power in Germany can be found in a study by the Umweltbundesamt (UBA; German Federal Environment Agency) [5]. It also contains a report on the statistical data base for CHP which is not complete.

[3] Source: Eurostat [6]

[4] Source: Eurostat [4]. Notes on the statistical methodology can be found here.

3.1 The specifics of combined heat and power generation

3.1–a Electric efficiencies and electricity loss during heat extraction

The deciding factor for the energy-related evaluation of CHP is at which temperature level the waste heat of the heat engine initially accumulates. Two cases need to be distinguished in this regard:

(1) Facilities with high electric efficiency but electricity loss during heat extraction:
Steam turbine power plants and particularly the so-called combined cycle power plants (CCPP) belong to this category where the waste heat of a gas turbine accumulating at a still very high temperature level is fed into a downstream steam turbine power plant.

The conversion of fuel heat into electricity via a steam turbine process has been technologically perfected to a large extent. At the "hot end", during the transfer of the combustion heat onto the working substance at very high temperatures, unavoidable exergy losses occur, however, as both the boiler and the steam conducting pipes must not exceed a maximum temperature, thus limiting the achievable steam temperature. However, the highest working temperature has been continuously increased via the improvement of material properties. Today, 600°C can be reached and 700°C are aimed for by technological developments (cf. chapter II.1).

At the "cold end" of the process the low-pressure turbine expands the steam against a very small back pressure which is only determined by the temperature of the re-cooling medium in the condenser. Also, when re-heating the working substance, a smart process control ensures that the temperature differences between the particular heat source and the working medium remain as low as possible during the entire heating-up process via cleverly devised preheating and intermediate overheating.

If heat from this process, which is optimised for the low temperature regime in particular, is diverted not at the temperature level of the available cooling water (e.g. 30°C) but at the considerably higher level of the inlet flow temperature of district heating (90 to 150°C or higher), the exergy (cf. chapter I.2) still contained in the water for district heating can no longer be utilised for electricity generation, and the electric efficiency decreases accordingly.

The electric efficiencies of modern coal-fuelled power plants, usually designed as pure steam turbine power plants, are currently at about 45%, and 50% are aimed at. Modern gas power plants, however, are increasingly operated as combined cycle power plants (CCPP). Thus, an electric efficiency of 58% [8] is currently reached and facilities aiming at 60% efficiency are already under construction [9][5].

(2) Facilities with low electric efficiency and direct use of waste heat:
Motor driven cogeneration plants, termed block-type thermal power plants (BTTP), and gas turbine plants belong to this category. Gas turbine plants achieve only an electricity yield of about 38% at the most due to their still high exhaust gas temperature. This is a comparatively small percentage for the precious energy carrier natural gas. Also in BTTPs, the exhaust gas and motor waste heat of the petrol and diesel engines already accumulate at such a high temperature level that the electric efficiency is only slightly more than half to, at best, approaching two thirds, of the electric efficiency of a technologically optimised CCPP, i.e. it is comparatively poor. In these facilities one has therefore, right from the start, dispensed with the utilisation of

[5] The optimum efficiencies measured under standardised conditions, however, are frequently not reached in industrial practice where seasonal cooling conditions, deviations from the optimum working point, frequent powering up and down of the plant, as well as aging play a role. In this chapter we take the optimum nominal efficiencies of CHP plants as well as power plants, as a basis for our fundamental future-oriented considerations (amongst other things because only those numbers are generally accessible).

the low temperature region for electricity generation, although it would be thermodynamically advisable. Of course, it is convenient that the waste heat, initially accumulated at a wastefully high temperature level, can still be utilised as district heat.

Recently, smaller, mostly motor-driven, CHP plants have been developed for heating of individual buildings. That is, heat is decentrally produced there, i.e. directly at the heat consumer's location as is the case with usual firing installations. In view of the task the term "electricity generating heating" (EGH) is therefore quite appropriate; in view of the applied technology, however, EGH systems can be regarded as small block-type thermal power plants, i.e. as mini- or even micro-BTTP. Small diesel or petrol engines have efficiencies ranging from about 20% to 30% which can also be found in similarly small automotive engines. It comes as no surprise that they are even worse than the electric efficiencies of the larger stationary plants in the BTTP designed for district heating (30 to 35%).

3.1–b Centralised and decentralised facilities

A facility is called "decentralised" if the heat is fed directly into the space heating system at the place of generation, and "centralised" if the generated heat is delivered via district heating pipes. The following properties can then be assigned:

(1) Decentralised CHP

- Low inlet temperatures are reachable if the building is thermally renovated and the radiators are dimensioned spaciously (particularly advantageous to surface heating).
- As a consequence, return temperatures are so low that exhaust gas condensation is possible inside the CHP unit or in a separate exhaust gas heat exchanger (e.g. also as chimney heat). The residual heat of the exhaust gas can be utilised to a large extent and thus heat utilisation comparable to that of a condensing boiler[6] is possible.
- By making individual adjustments to the inlet temperature the exergetic saving potential is fully used.
- Decentralised feed-in of electricity helps to avoid grid losses.
- Electricity generating heating (EGH) is, for example, a genuine decentralised CHP [10].

(2) Centralised CHP

- A high inlet temperature is necessary which is set by the consumer with the highest demands within a heat grid for district heating in accordance with the convoy principle. Furthermore, temperature differences at the heat exchangers and the cooling down up to the last consumer must be taken into account. As district heating must ensure hot water supply at all times, it is not possible to use low inlet temperatures even when supplying a purely residential area.
- A low return temperature is not possible as all (warm or cold) return flows are mixed. It thus follows: When applying centralised district heating it is usually not possible to utilise the upper heating value of the fuel.
- Considerable investments for constructing a heat grid for district heating, especially as areas with a high density of heat demand are already connected in most cases.
- Additional operating costs for pumps and due to pipe losses.

Conclusion: Decentralised electricity generating heating is characterised, albeit at lower electric efficiencies, by an (at least possible) heat utilisation similar to that of a condensing boiler. In contrast, a (centralised) heat

---

[6] As opposed to earlier boilers, condensing boilers in use since the mid-1990s also utilise the latent heat of the water vapour contained in the exhaust gases by lowering their temperature; for natural gas, it amounts to 11% of the lower heating value. This way, efficiencies above 100% are reached as the heat produced is referred to the lower heating value. (The condensing boiler heating value of natural gas is 111% of its lower heating value.)

supply via district heating is characterised by poor heat utilisation at slightly better electric efficiencies.

<u>3.1-c CHP in summer and winter</u>

The basic dilemma of cogeneration is caused by the seasonal fluctuation in the heat demand for heating buildings. Industrial applications are only marginally affected and for this reason the most effective CHP facilities are found in the industrial sector. In the future, an increased application of adsorption chillers could lead to some heat utilisation for the air-conditioning of buildings in the summer. Due to the remaining high seasonal fluctuations in heat demand the facility in question must:

- either provide only a medium size share of the heat demand and leave a sizable remainder to the peak load boiler
- or provide a large share of the heat demand, but needs to earn its money from peak electricity because of the small number of peak load hours in CPH operating mode.

Both alternatives have a negative effect on the energy balance for centralised supply via district heating.

In the decentralised case, the peak load boiler in the first mentioned alternative does not result in an energy deficit of a condensing boiler is used. However, because of its particularly low electric efficiency, any peak electricity generation has a particularly negative effect on the energy balance.

The low capacitiy utilisation is a serious economic factor for cogeneration which will not be examined further in the present study.

3.2 Comparison: natural gas CHP and separate generation of electricity and heat

In this section we will compare, for the primary energy carrier natural gas, different CHP facilities to the separate generation of electricity in a CCPP power plant and heat in a condensing boiler or via heat pumps. In doing so, we envisage the following modernisation scenario: Some existing older power plants and a large number of old space heating systems are to be replaced with modern natural gas facilities. We will examine new CPH facilities and compare them to two reference cases:

(1) CHP case study:
Old space heating systems and old power plants are replaced with new CHP facilities and with additional peak load boilers usually needed for full heat supply. Heat grids for district heating transport the heat from CHP facilities to the locations of the replaced space heating systems.

(2) First reference case (see subchapter 3.2-a):
The old boilers are replaced with modern natural gas condensing boilers, and additional natural gas CCPP power plants are built which are to supply the same amount of electricity as the CHP facilities of the case study.

(3) Second reference case (see subchapter 3.2-b):
The old boilers are replaced with modern heat pumps and additional CCGT power plants are built which are to supply the amount of electricity of the CHP facility of the case study plus the amount of electricity required to operate the heat pumps.

The energy flow diagram of the CHP provider is shown in Fig. 1: During the billing period (for instance, one year) the heat from natural gas, Q_0^P, feeds the CHP facility and the peak load boiler with the shares indicated in Fig. 1.

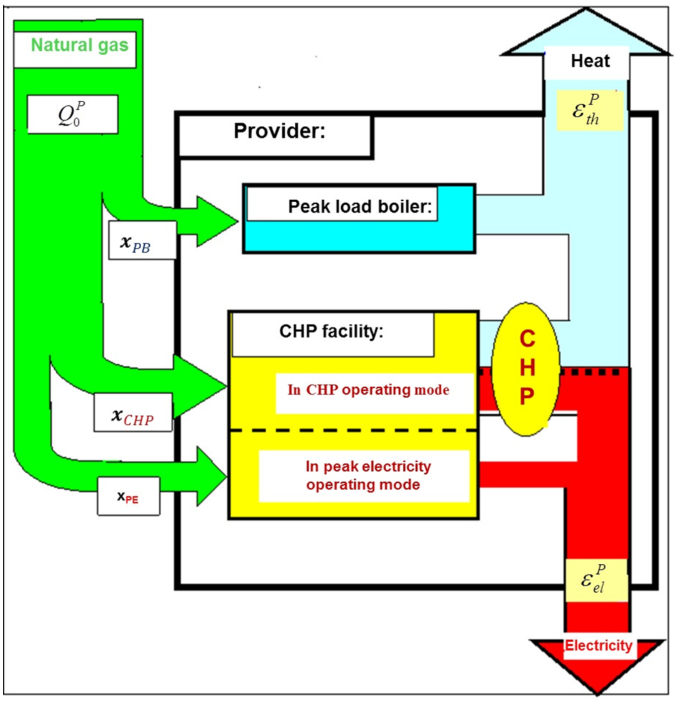


Fig. 1: Complete heat and electricity generation by a district heat provider.

The CHP facility consumes a part x_{CHP} of Q_0^P when in genuine CHP mode where electricity and useful heat are cogenerated, and a part x_{PE} for the occasional supply of peak electricity without heat utilisation; the provider requires the remaining part x_{PLB} of the natural gas input Q_0^P for operating the peak load boiler at those times when the CHP facility can no longer meet the heat demand by itself. Apart from the commonly emphasised genuine CHP mode (the "showpiece mode"), the occasional supply of peak electricity and heat from peak load boilers must not be forgotten when making up a complete energy balance. Altogether, the CHP provider converts the primary energy input Q_0^P into heat with a thermal efficiency of ε_{th}^P, and into electricity with an electric efficiency of ε_{el}^P. The total fuel utilisation by the CHP provider is the sum of:

$$\varepsilon_{tot}^P = \varepsilon_{el}^P + \varepsilon_{th}^P .$$

3.2–a Comparison with combined cycle power plant (CCPP) and condensing boiler

Separate generation is described by the electric efficiency of the CCPP η_{el}^{CCPP} and by the thermal efficiency of the condensing boiler for which 105% is equated (see [1], section 6.21).

Insert: Derivation of the primary energy factors *([1], [3])*

Fig. 1 depicts the connection between the conversion efficiencies ε or η and the average annual shares x on the one hand and the heat output H^P, the electric output E^P, and the primary energy input Q_0^P on the other hand within a CHP facility:

(1) $$H^P = \varepsilon_{th}^P Q_0^P \text{ with } \varepsilon_{th}^P = (\eta_{th}^{CHP} x_{CHP} + \eta_{th}^{PB} x_{PB})$$

(2) $$E^P = \varepsilon_{el}^P Q_0^P \text{ with } \varepsilon_{el}^P = (\eta_{el}^{CHP} x_{CHP} + \eta_{el}^{PE} x_{PE})$$

(3) $$\varepsilon_{tot}^P = \varepsilon_{el}^P + \varepsilon_{th}^P$$

(4) $$x_{CHP} + x_{PB} + x_{PE} = 1.$$

The subscripts *CHP, PB,* and *PE* refer to cogeneration, heat production via the peak load boiler and the separate electricity peak respectively; the superscript *P* stands for the provider (i.e. the CHP facility) and the subscripts *th, el,* and *tot* stand for thermal, electric, and total respectively. During separate generation the primary energy of the CCPP power plant, $Q_0^{(E)}$ is utilised with an efficiency of η_{el}^{CCPP} and the primary energy of the condensing boiler $Q_0^{(H)}$ with an efficiency of η_{th}^{CB}:

(5) $$H = \eta_{th}^{CB} Q_0^{(H)}$$

(6) $$E = \eta_{el}^{CCGT} Q_0^{(E)}$$

In a detailed comparison, one sets $H^P = H$ and $E^P = E$ and calculates the ratio f of the primary energy consumption $Q_0 = Q_0^{(H)} + Q_0^{(E)}$ of separate generation to that of the provider Q_0^P. One adds the equations (1)=(5) und (2)=(6) and, taking into account eq. (3), calculates the ratio

(7) $$f = \frac{Q_0}{Q_0^P} = \frac{\varepsilon_{tot}^P}{\eta_{th}^{CB}} + \varepsilon_{el}^P \left(\frac{1}{\eta_{el}^{CCPP}} - \frac{1}{\eta_{th}^{CB}} \right)$$

The primary energy factor f characterises the additional input of primary energy for separate electricity and heat generation. The efficiencies ε^P of the provider take into account the shares of primary energy x_{PB} and x_{PE} for the peak load boiler and separate electricity supply respectively. In terms of pure cogeneration, i.e. x_{PB} = x_{PE} = 0, f becomes the primary energy factor f_0 of this “showpiece mode”:

(8) $$f_0 = \frac{\eta_{tot}^{CHP}}{\eta_{th}^{CB}} + \eta_{el}^{CHP} \left(\frac{1}{\eta_{el}^{CCPP}} - \frac{1}{\eta_{th}^{CB}} \right),$$

where $\eta_{ges}^{CHP} = \eta_{th}^{CHP} + \eta_{el}^{CHP}$ is the overall fuel utilisation for pure cogeneration. The effect of the shares x_{PB} und x_{PE} can be demonstrated if one describes the primary energy factor f of the provider by the shares x_{PB} und x_{PE} as well as the factor f_0 of the showpiece mode. Taking into account eq. (1) to (3) and in accordance with eq. (8), the eq. (7) then reads

(9) $$f = f_0 - x_{PB}\left(f_0 - \frac{\eta_{th}^{PB}}{\eta_{th}^{CB}}\right) - x_{PE}\left(f_0 - \frac{\eta_{el}^{PE}}{\eta_{el}^{CCPP}}\right).$$

The primary energy factor f is, thus, a linear function of the primary energy shares x_{PE} (electricity) and x_{PB} (heat) by which the actual operating mode of the provider deviates from the pure cogeneration mode.

As a reference they are supposed to generate the same amount of electricity and useful heat which the producer of district heating supplies. From this detailed identity the respective fuel input can be calculated and added up to yield the total fuel input Q_0 of separate electricity and heat generation. In the following, the ratio of Q_0 to Q_0^P is termed the primary energy factor f

$$f = Q_0 / Q_0^P.$$

Thus, the primary energy saving by the CHP provider is

$$(Q_0 - Q_0^P) / Q_0 = 1 - 1 / f.$$

In the German law which defines the subsidies for CHP facilities, only the pure CHP mode (the "showpiece mode") is considered. The primary energy factor f then relates to the particular case for which the primary energy, which the provider feeds in for peak electricity and peak heat, is excluded from the consideration. This means that in our calculation the shares x_{PE} and x_{PB} are set to zero. The resulting primary energy factor for this showpiece mode is termed f_0.

When assessing CHP with regard to state subsidies, PES, the primary energy saving in the genuine CHP mode, is used in accordance with the EU Directive 2004/74/EC [11]. It is

$$PES = 1 - 1 / f_0 .$$

A system comparison between CHP and separate electricity and heat supply needs to take the peak load boiler of the CHP provider into account which barely exceeds an efficiency of 90% in a heat grid for district heating. The peak load boiler is in competition with the decentralised condensing boiler with η_{th}^{PB} = 105%. It is interesting, therefore, to directly show the effect of the shares x_{PB} and x_{PE}.

As an example, Fig. 2 gives the factor f for the energy input for separate generation of electricity and heat as a function of x_{PB}, the share of the energy input for the peak load boiler, for the 1 MW CHP facility "BHKW_1M" listed in Table 1. The individual parallel lines correspond to various shares of the generated peak electricity whose share x_{PE} can be calculated from the gas input necessary for this purpose.

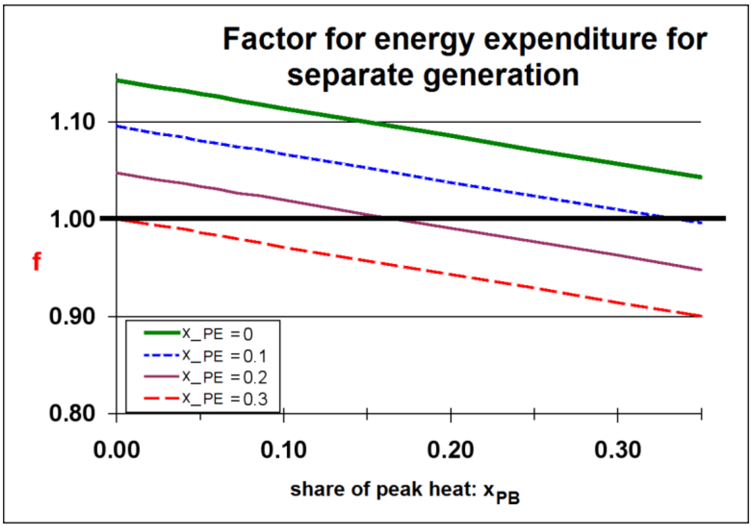


Fig. 2: Effects of peak heat and peak electricity on the factor *f*.
Comparison of "BHKW_1M" listed in Table 1 with CCPP (η_{CCPP} = 0.585) and condensing boiler (η_{CB} = 1.05).

For the showpiece mode with no peak heat (x_{PB} = 0) and no peak electricity (x_{PE} = 0) an additional energy input of 14% (f_0 = 1.14) is needed for separate generation. This additional energy input is reduced and even turns into a saving, when the share of the peak heat, x_{PB} , increases. Although the BTTP shown in Fig. 2 is a very advanced facility (at 39% the electric efficiency of the motor is very high), an additional energy input of only 14% for separate generation is the result even for the showpiece mode, i.e. the strictly heat led operating mode without an additional peak load boiler. In the centralised supply via district heating, the latent heat of natural gas can neither be utilised in the CHP facility nor in the peak load boiler. Fuel utilisation thus reaches only 89% even in the showpiece mode (see Table 1, column 3).

It is reasonable to suppose, considering such an advantageous electric efficiency, that the BTTP does not feed its electricity into the grid only when there is heat demand. From an assumed share of x_{PB} = 16% for the peak load boiler and x_{PE} = 20% for peak electricity generation follows f =1.0 (Fig. 2), i.e. in this case even this advanced CHP facility does not have an advantage over the reference case in terms of energy.

We will now consider a selection of natural gas fuelled CHP facilities and compare them to the reference case of separate generation of electricity in a combined cycle power plant (CCPP) and of decentralised heat in a condensing boiler. For this purpose we have used the examples[7] listed in the aforementioned study by the German Federal Environment Agency (UBA) [5] and added a natural gas back-pressure CHP (200 MW) [8] and a modern mini BTTP utilising the upper heating value (MEPHISTO, 20 kW) [10].

	CHP facility in co-generation operating mode and in peak load operating mode								Provider, total			
	Co-generation operating mode				Separate peak with $x_{PE} = x_{PB} = 0.1$				(see fig. 1)		fuel utili-sation	PE factor separate generation
Electricity/heat producer	η_{el}	η_{tot}	Source of input data	f_0	η_{PE}	x_{PE}	η_{PB}	x_{PB}	ε_{el}	ε_{th}	ε_{tot}	f
CCPP	0.585	0.585	A		0.585	1	0	0	0.585	0	0.585	
GegenP200M	0.460	0.90	A	1.21	0.46	0.1	0.90	0.1	0.41	0.44	0.86	1.13
GuD Erdgas,100 MW	0.445	0.89	B	1.18	n.s.	0.1	0.90	0.1	n.s.	0.45	n.s.	n.s.
BHKW_1M	0.390	0.89	B	1.14	0.390	0.1	0.90	0.1	0.35	0.49	0.84	1.07
Mephisto_20k	0.315	1.05	C	1.24	0.32	0.1	1.05	0.1	0.28	0.69	0.98	1.14
GuD24M	0.363	0.86	B	1.09	n.s.	0.1	0.90	0.1	n.s.	0.49	n.s.	n.s.
GT_10M	0.311	0.83	B	1.03	0.311	0.1	0.90	0.1	0.28	0.51	0.79	0.96
BHKW_50k	0.293	0.88	B	1.06	0.293	0.1	0.90	0.1	0.26	0.56	0.82	0.98
Mikro_9k	0.243	0.98	B	1.12	0.243	0.1	0.98	0.1	0.22	0.69	0.91	1.03
Mikro_3k	0.157	0.94	B	1.01	0.157	0.1	0.94	0.1	0.14	0.72	0.86	0.93
Mikro_0.8k	0.104	0.90	B	0.94	0.104	0.1	0.90	0.1	0.09	0.73	0.82	0.85
Condensing boiler	0	1.05			0	0	1.05	1	0	1.05	1.05	
Standard boiler	0	0.90			0	0	0.90	1	0	0.9	0.9	

Table 1: Comparison of CHP facilities of different sizes ranging from 200 MW_{el} to 0.8 kW_{el} with separate electricity generation in a combined cycle power plant (CCPP) and of heat generation in a condensing boiler (see [1] for details of the calculations). Input data sources: A = [8], B = [5], C = [10]

Table 1 provides an overview of the basic properties of these facilities. The PE-factor for separate electricity and heat generation is initially calculated for the showpiece mode of the cogeneration mode, i.e. the factor f_0 (column 5); then the effect of peak electricity and peak heat generation on the PE-factor f (last column) of the overall provider is presented for the example $x_{PB} = x_{PE}$ = 0.1. (The general case is discussed in [1].)

[7] Loc. cit., study by the Umweltbundesamt (UBA; German Federal Environment Agency), p. 158, Tab. 5.1

From Table 1 the following conclusions can be drawn:

- The additional input of primary energy for separate generation of electricity in a modern combined cycle power plant (CCPP) and of heat in a properly adjusted condensing boiler rarely exceeds 20% even in the showpiece mode of the genuine CHP mode of the facility; in some cases, however, it is not even 10%.
- When correctly including the peak load boiler which is needed by the CHP provider if the facility is designed well and when taking the peak electricity without heat utilisation into account, the result is a significant loss of advantage on the CHP side. For the given example of a fuel input of 10% for both peak electricity and peak heat, a significant advantage of CHP can basically only be found for individual cases.

Regarding the choice of x_{PE} *and* x_{PB}: There is no statistical basis for the comprehensive survey of the fuel shares of separate uncoupled electricity (x_{PE}) and uncoupled heat generation (x_{PB}) used in practice. The chosen example $x_{PE} = x_{PB} = 0.1$ describes a slight deviation from genuine cogeneration. Even this slight deviation results in the aforementioned loss of advantage on the CHP side when compared with separate generation.

In conclusion: Electricity and heat supply via CHP facilities is not always superior to separate supply. Not only the facilities themselves but also, to a large extent, the operating mode is what matters.

<u>3.2–b Comparison with combined cycle power plant (CCPP) and electric heat pump</u>

Thermodynamically optimised heating can be realised either with CHP or with heat pumps. A CHP facility with dedicated waste heat utilisation at the temperature level of the heat application could barely be improved when thermodynamic processes take place close to the optimum. In industrial practice with a well-defined steam demand a strictly heat led (!) CHP will usually remain peerless in terms of energy.

The situation is different with regard to buildings: In district heating, due to the convoy principle and other restrictions (see [1] subchapter 6.2) no qualitative advantage can be gained from the efforts to reduce the exergetic demands of a single building. On the other hand, when employing individual heat pumps, any progress with regard to reducing the exergetic demands of thermal heat (i.e. low inlet temperature, low return temperature, utilisation of heating-up processes, small temperature differences at the heat exchangers, see chapter I.2) can be immediately converted into a higher efficiency of the heat pump.

As a comparison to natural gas demand Q_0^P of a CHP provider we will, as a reference case, now examine the natural gas input Q_0 in a combined cycle power plant (CCPP) which feeds the same amount of electricity into the grid as the CHP facility (CHP mode and peak electricity) and also meets the electricity demand of the decentralised heat pumps which together supply the same amount of heat as the district heating provider. That is, we will compare the gas input required for operating both supply systems for exactly the same supply task.

The following ties in with the equations given above when the thermal efficiency of a condensing boiler, η_{th}^{CB}, given above is replaced with η_{th}^{HP}, i.e. the thermal efficiency of the heat pump related to the natural gas input in CCPP power plants. The quantity η_{th}^{HP} is the product of the efficiency η_{el}^{CCPP} of the power plant and the annual performance factor, APF, of the heat pump:

$$\eta_{th}^{HP} = \eta_{el}^{CCPP} \cdot APF$$

In the system comparison, the heat pump thus acts as a “super boiler” with an exceptional thermal efficiency η_{th}^{HP}. Table 2 lists some relevant figures which must be read in comparison with the thermal efficiency of a condensing boiler, at best η_{th}^{CB} = 1.1. Combining CCPP power plants and heat pumps yields high thermal efficiencies for the centralised natural gas input in the power plant for the purpose of decentralised heat generation.

APF	3	3.5	4	4.5	5	5.5
η_{el}^{CCPP}	0.585	0.585	0.585	0.585	0.585	0.585
η_{th}^{HP}	1.76	2.05	2.34	2.63	2.93	3.22

Tab. 2: Effective thermal efficiency of heat pumps in terms of natural gas consumption of the modern electricity producer (CCGT) as a function of its annual performance factor.

We will now compare the CHP facilities listed in Table 1 to separate generation of electricity in a CCPP power plant and of heat via heat pumps which receive their electricity from the considered CCPP power plant. Our basis is a good annual performance factor (APF) of 4 – which will probably be no more than mediocre in the future – and a corresponding η_{th}^{HP} = 2.34. In Table 3, the PE factors for separate electricity and heat generation are again initially calculated for the pure cogeneration mode, i.e. the factor f_0, and the effect of peak heat and peak electricity generation on the PE-factor f of the overall provider is presented for the example $x_{PB} = x_{PE} = 0.1$.

Table 3 shows that all CHP facilities considered are inferior to the combination of CCPP power plants and heat pumps, even in the showpiece mode (without peak heat and peak electricity). CHP facilities with a high electric efficiency, e.g. the 200 MW back pressure plant, “GegenP_200M”, can, at f_0 = 0.97, still almost compete with separate generation in the showpiece mode, but the feed-in of heat via the peak boiler and the peak electricity further worsen the PE balance.

	CHP facility in co-generation operating mode and in peak load operating mode								Provider, total			
	Co-generation operating mode				Separate peak with $x_{PE} = x_{PB} = 0.1$				(see fig. 1)		fuel utili-sation	PE factor separate generation
Electricity/heat producer	η_{el}	η_{tot}	Source of input data	f_0	η_{PE}	x_{PE}	η_{PB}	x_{PB}	ε_{el}	ε_{th}	ε_{tot}	f
CCPP	0.585	0.585	A		0.585	1	0	0	0.585	0	0.585	
GegenP200M	0.460	0.90	A	0.97	0.46	0.1	0.90	0.1	0.414	0.44	0.86	0.90
GuD Erdgas,100 MW	0.445	0.89	B	0.95	n.s.	0.1	0.90	0.1	n.s.	0.45	n.s.	n.s.
BHKW_1M	0.390	0.89	B	0.88	0.390	0.1	0.90	0.1	0.351	0.49	0.84	0.81
Mephisto_20k	0.315	1.05	C	0.85	0.315	0.1	1.05	0.1	0.284	0.69	0.98	0.78
GuD24M	0.363	0.86	B	0.83	n.s.	0.1	0.90	0.1	n.s.	0.49	n.s.	n.s.
GT_10M	0.311	0.83	B	0.75	0.311	0.1	0.90	0.1	0.280	0.51	0.79	0.69
BHKW_50k	0.293	0.88	B	0.75	0.293	0.1	0.90	0.1	0.264	0.56	0.82	0.69
Mikro_9k	0.243	0.98	B	0.73	0.243	0.1	0.98	0.1	0.219	0.69	0.91	0.67
Mikro_3k	0.157	0.94	B	0.60	0.157	0.1	0.94	0.1	0.141	0.72	0.86	0.55
Mikro_0.8k	0.104	0.90	B	0.52	0.104	0.1	0.90	0.1	0.093	0.73	0.82	0.47
Condensing boiler	0	1.05					1.05	1				
Heat pump	0	2.34										

Tab. 3: Comparison of the CHP facilities listed in Table 1 to the separate generation of electricity from centralised combined cycle power plants (CCPP) and heat pumps fed by them. (For details see [1].) Input data sources as given in Table 1.

Conclusion: CHP is inferior in terms of energy when competing with a combination of CCPP power plants and heat pumps and will probably fall even further behind in the future, given that buildings and heating devices have a considerable potential for improvements in relation to thermodynamically optimised heating.

3.2-c Summary of subchapter 3.2:

A detailed comparison of various natural gas-CHP facilities (facilities for both centralised supply with district heating and decentralised heat supply) to the separate supply of electricity and heat using natural gas has yielded:

- Separate generation via CCPP power plants and condensing boilers is generally only slightly worse than CHP and can sometimes even be better, depending on the operating mode of the CHP.

- When applying efficient heat pumps fed by CCPP power plants there generally is a considerable advantage over CHP in terms of energy.

This comparison is a basic physical argument. It disregards side effects such as heat loss in heat grids for district heating, non-operation periods, electric losses, additional input for decentralised gas supply, required electricity for pumps or the like, which can at times make a difference in practice. It is assumed, however, that efficient, natural gas fuelled CCPP power plants and (condensing) boilers or heat pumps are used.

The central point of the physical argument is the following: When generating electricity and heat for a specific purpose (i.e. heating up a specific amount of heat to a certain temperature level) it is not only the degree of fuel utilisation that matters. Rather, there are systems consuming less fuel in total as they have high efficiencies for generating electricity and more accurately meet the demands of heat.

3.3 Combined heat and power generation: energy policies and public debate

CHP is state-subsidised since it is assumed that it can save a significant amount of energy and CO_2 as opposed to separate heat and electricity generation (see e.g. [12]), something which is being called into question in this chapter.

A CHP facility considered for subsidisation can be formally compared with a multitude of heat and electricity providers. Utilising this spectrum of possibilities, it is possible to calculate very favourable figures for CO_2 saving of about 25-40%, sometimes even more, with regard to CHP[8]. This results in a factor of 1.3 to 1.6 and higher for the (mostly presented) additional energy input required for separate generation as opposed to CHP[9]. Politicians as well as the public have high expectations with regard to CHP saving potential. Accordingly, the German government has decided to double the share of electricity generated by CHP from 12% today to 25% in 2020. It subsidises investments in and the operation of CHP facilities as per the German CHP law (KWK-Gesetz) [7] and the German Renewable Energy Sources Act (EEG) [13]. With these laws, CHP is given preferential treatment over other forms of energy- and CO_2-saving. In chapter 3.2 we compared the energy supply via new CHP facilities to that via alternative, new facilities for separate electricity and heat generation. We found the savings with CHP to be considerably lower than previously made public.

---

[8] Cf., for example, the promotional flyer by the Bundes-Umweltministerium (BMU; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) [12]

[9] The primary energy factors f_0 and f found in Tables 1 and 3 also refer to the additional input of separate generation as opposed to co-generation.

What did we do differently?

Most conventional considerations differ from ours in one or more of the following aspects:

(1) Often, comparisons are made between non-equivalent quantities:

- heat (low exergy content) and electricity (pure exergy) are simply added and this "fuel utilization" is subsequently used as the sole quality factor,
- electricity from CHP using natural gas is compared with electricity from coal fuelled power plants,
- new CHP facilities are compared with old power plants and boilers,
- one is pleased by "waste heat" utilisation and overlooks the fact that it is bought via a serious loss of electric efficiency.

(2) Only the heat from the CHP facility is considered and not the entire supply of district heating. – The contribution of the peak load boiler is thus left out of the evaluation in spite of the fact that it needs to be part of the energy balance (even though it reduces the district heating efficiency).

(3) Not the overall electricity generation in the CHP facility but simply the electricity generation in ideal heat led operating mode with cogeneration of electricity and heat is evaluated. Conventional electricity generation without heat utilisation, also possible via a CHP facility, is left out. – A CCPP power plant scores over a BTTP especially with regard to genuine electricity generation. If, however, German electricity supply is increasingly based on new CHP facilities rather than on additional CCPP power plants, outdated power plants or genuine CHP facilities need to take over the role of the CCPP power plants not built and occasionally generate electricity without heat utilisation. This aspect, therefore, must not be left out of the balance.

(4) The efficiencies actually reached by modern CCPP power plants and condensing boilers are not used as comparative values for separate generation in Germany, but rather the significantly lower (by about 10%) "European" comparative figures of the EU Commission Decision 2007/74/EC [14].

(5) With regard to heat pumps, one assumes that electricity is supplied by the German electricity mix. Instead, we take the electricity supply from a CCPP power plant as the basis in our system comparison. – A new natural gas CHP facility generates both electricity and heat using a **newly** built facility and natural gas. For an exact system comparison with separate generation, natural gas facilities also need to be modern. This approach, already set out in the EU Directive 2004/8/EC [11] for power plants and decentralised boilers, must also be applied to electricity supply for decentralised heat pumps. If, in the system comparison, the decentralised heat pumps were fed via the electricity mix, it would actually be the fuel mix of German electricity generation rather than natural gas that is used for the energy supply of the heat pumps. Furthermore, the intended shifting of natural gas from decentralised heat generation to electricity generation will in fact result in new CCPP power plants being built if CHP facilities are used to a smaller extent.

(6) The side effects already mentioned in subchapter 3.2-c are taken into account. – In principle, there are no objections to this approach. As these side effects partly compensate each other, however, and are mostly given in general terms, they are left out of the considerations of this study which focus on the basic physical principles. This allows for a simpler presentation and makes the effect of the essential parameters clearer.

3.3-a State subsidisation

State subsidisation of a CHP facility requires a comparative calculation which proves energy savings. With regard to national criteria for CHP subsidisation, the EU has codified two important and rather self-evident principles in its Directive EU 2004/8/EC [11] (see [1] section 5, Fig. 7):

- only facilities utilising the same primary energy source may be compared;
- when comparing with the separate generation of heat and electricity the best available and economically justifiable technology is to be used.

The second principle was somewhat weakened when specific figures were given in the EU Decision 2007/74/EC [14] for the “best technology”. An assessment shows that the formally stated comparative efficiencies of the gas power plant and the gas boiler are lower by about 10% when compared with the state of the art technology currently available. A “highly efficient” natural gas CHP facility, worthy of subsidisation according to the Directive, must yield 10% primary energy savings when measured against the technologically outdated facilities, and therefore actually needs to be only as efficient as separate generation of electricity in a centralised CCPP power plant and of heat in a standard condensing boiler in Germany. The term “highly efficient” thus is inappropriate and confusing, subsidisation already begins at the status quo (for details see [1], section 6).

Small-scale CHP facilities are considered to be “highly efficient” and thus worthy of subsidisation as per the Directive EU 2004/8/EC [11], as soon as they yield any numerical energy savings. If the comparative values are taken into account, having been set too low as mentioned above, small-scale CHP facilities may be subsidised even when they need significantly more primary energy than separate generation.

3.3-b CHP operating mode and further savings

A large investment already made into heat supply hinders motivation and the cost-effectiveness of further energy saving measures.

In a residential area, it makes sense to connect to district heating in a coordinated and concentrated fashion even if there is no compulsion to connect to the grid. For this reason, many households will not implement thermal renovation of buildings in a timely manner due to the expense, even though it would best be done on the occasion of the change-over to the new heating system. A renovation in retro reduces the capacity utilisation and thus the cost-effectiveness of the district heating.

The investment costs for a decentralised CHP are covered to a considerable extent by the electricity sales revenues. An initially optimally designed CHP facility will supply less “heat led” electricity when thermal renovation is done in retro. The desired low heating costs are juxtaposed with low electricity sales revenues. Revenues for the owner's use of electricity are particularly high: the small-scale electricity producer can credit himself for the expensive household tariff and the additional CHP subsidisation; his facility can offset the operating costs without heat utilisation even at a medium electric efficiency. The producer, therefore, is mainly interested in a high capacity utilisation of his CHP facility; for him, a thermal renovation is uneconomic. CHP, therefore, is in danger of becoming an ecological dead end.

When a home owner plans to install a heat pump, which naturally needs to be designed individually, he will be advised, already at the planning and design stage, to reduce the operating costs of his facility via thermal renovation. Saved operating costs are not juxtaposed with loss of revenues which might hinder motivation as in the case of CHP, when a renovation takes place in retro.

3.4 Outline for the optimisation of the use of natural gas for building heat

Cogeneration is a modern and thermodynamically demanding form of generating final energy from fuels. A general worthiness of subsidisation solely based on the CHP process, however, cannot be asserted due to energy saving reasons. CHP facilities should face the competition from regular energy and CO_2 saving. For this reason, the question of optimisation should be posed in the appropriate generality: How and in which general context can natural gas be utilised most efficiently either directly or indirectly for building heat supply? For this purpose, the right signals must also be sent with regard to the subsidisation and speeding up of the optimisation necessary.

3.4–a Proposal: Savable energy as a criterion for subsidisation

CHP facilities are subsidised in Germany according to the principle "all or nothing": either the prerequisites of the CHP law are met resulting in full subsidisation for each kWh generated in this mode of operation as "CHP electricity", or there is no subsidisation at all. Since the requirements of the CHP law are very low, as mentioned above, it does happen that a facility consuming more natural gas than an equivalent one for separate generation is nevertheless fully subsidised.

The principle of "all or nothing" is also used for the feed-in tariffs for renewable energies as per the German Renewable Energy Sources Act (EEG). This is justified here for it does not matter how efficient the facilities utilising renewable energies are: each kWh generated *without emitting* CO_2 replaces one *emitting* CO_2, and renewable energies (with the exception of biomass) are plentiful.

With regard to CHP the situation is completely different: scarce energy sources are being used and the savings effect does not show in the generated amount of electricity but needs to be calculated as the difference to the reference facilities for separate electricity and heat generation.

What is more obvious, then, than taking this proven savable energy as the criterion for subsidisation? If subsidisation is desired at all, we argue against the hitherto existing flat rate and for a "linear tariff" with regard to energy saving. This linear saving tariff can be differentiated according to the energy carriers used and applied to all types of thermodynamically opitimised heat generation in the same way. This allows for fair market competition.

3.4–b Outline of an integrated concept for the utilisation of natural gas with the following aims

(1) Reducing direct use of natural gas in buildings by means of:

- thermal renovation of the building skin and recuperation of heat,
- design of heat exchangers (radiators, surface heating) for small temperature differences with regard to room temperature,
- use of heat pumps,
- use of solar energy for hot water generation in summer and for supporting low temperature heating systems in winter.

(2) Increasing the use of natural gas for electricity generation by constructing new centralised highly efficient combined cycle power plants (CCPP) which are intended to:

- indirectly take over a large part of the heat supply by driving decentralised heat pumps,
- provide district heating via heat extraction in line with demand,
- replace old power plants with high specific CO_2 emissions in part and base load.

(3) Utilising natural gas for decentralised CHP, but only when the effect of the higher heating value is exploited and the strictly heat led operating mode is guaranteed. Then, decentralised CHP can make a contribution to the seasonal peak load via the increased use of heat pumps in an economically sensible way.

3.5 Summary and outlook

In the past, politicians and the general public over-emphasised the advantages of CHP and obviously did not sufficiently consider its disadvantages. The aim of this study is to adjust the measuring scale to the modern situation using the example of natural gas fuelled facilities.

Even in the showpiece mode of a strictly heat led mode of operation without a centralised peak load boiler, CHP is usually able to save only small percentages of primary energy as opposed to separate generation of electricity (CCPP) and heat (condensing boiler). Taking into account the peak heat, which is economically advisable for a reasonable CHP design, and the temptation to provide peak electricity without heat utilisation, the savings effect approaches zero or even turns negative.

When comparing CHP to decentralised electricity generation from electric heat pumps, whose electricity is supplied by a CCPP power plant, CHP is noticeably inferior.

In order to better meet climate protection goals, an integrated overall concept of the thermodynamically optimised supply of the energy service “comfortable indoor temperature and hot water” is necessary. The state ought to support this development via research and development, pilot programmes and by assisting market introduction. In the framework of broad subsidisation, the state should not restrict it to particular technologies, but rather introduce a "linear savings tariff" which takes into account the provable energy savings in comparison with a demanding reference case.

Materials

This chapter is based on a comprehensive presentation as an “encyclopedia of materials” (Materialienband) as well as two power point presentations in which further details and sources are given.

[1] Gerhard Luther materials: *KWK und Systemvergleich* (German only; translation: *Co-Generation and System Comparison*) http://www.uni-saarland.de/fak7/fze/AKE_Archiv/DPG2010_E-Studie/

[2] Gerhard Luther: *Kraftwärmekopplung (KWK) – Hoffnungsträger oder Subventionsloch?* (German only; translation: *Co-Generation – Beacon of Hope or Swallowing Up Subsidies?*), 2008 http://www.uni-saarland.de/fak7/fze/AKE_Archiv/AKE2008H/Links_AKE2008H.htm

[3] Gerhard Luther: *Thermodynamisch optimiertes Heizen: KWK, Wärmepumpe und Systemvergleich* (German only; translation: *Thermodynamically Optimised Heating: Co-Generation, Heat Pump and System Comparison*), 2009 und 2010 http://www.uni-saarland.de/fak7/fze/AKE_Archiv/AKE2009H/Links_AKE2009H.htm und http://www.uni-saarland.de/fak7/fze/AKE_Archiv/DPG2010-AKE_Bonn/Links_DPG2010.htm

Notes and references

[4] Eurostat, scientific journal series *Umwelt und Energie* (*German only; translation: Environment and Energy*), issue 3/2006 ISSN 1562-3092, European Communities (2006).
http://www.eds-destatis.de/de/downloads/sif/nq_06_03.pdf (2002)

[5] M. Horn et.al. *Ermittlung der Potenziale für die Anwendung der KWK und der erzielbaren Minderung der CO_2-Emissionen einschließlich Bewertung der Kosten* (German only; translation: *Determining the Potential for Applying Cogeneration and the Attainable Reduction of CO_2 Emissions Including Cost Evaluation*) 318 p. (2007), Vol. 10/07 of the journal series by the UBA (Umweltbundesamt; German Federal Environment Agency) Climate Change, ISSN 1862-4359. It can be downloaded at: http://www.umweltbundesamt.de

[6] Eurostat, *Combined Heat and Power (CHP) in the EU*, 2007 data, scientific journal series *Data in Focus*, 28/2009, European Commission (2009).

http://www.eds-destatis.de/de/downloads/sif/qa_09_028.pdf (2007).

Eurostat, *Statistik über Kraft-Wärme-Kopplungsanlagen (KWK-Anlagen) in der EU im Jahre 2000*, (German only; translation: *Statistics on Cogeneration Facilities in the EU in 2000*), scientific journal series *Statistik kurz gefasst*, (German only; translation: *Statistics in short*), Topic 8-12/2003, ISSN 1562-3092, European Communities 2003.
http://www.eds-destatis.de/de/downloads/sif/nq_03_12.pdf (2000)

[7] KWKG: *Kraft-Wärme-Kopplungsgesetz 2009* (German law: act on combined heat and power generation 2009), Bundesgesetzblatt (Federal Law Gazette) Vol. 2009 Part I, p. 2870 et.seq.
http://bundesrecht.juris.de/bundesrecht/kwkg_2002/gesamt.pdf

[8] Voss 2009: *Referenzdatensatz für Kraftwerke* (German only; translation: *reference data set for power plants*) as of 31 July 2009, private communication

[9] E.ON Kraftwerke GmbH 2009 (E.ON power plant company): Homepage regarding the construction of the power plant Irsching
http://www.kraftwerk-irsching.com/pages/ekw_de/Neubau/Bauvorhaben/index.htm

[10] Gas fuelled compact BTTP MEPHISTO G20+
http://www.kraftwerk-bhkw.de/MEPHISTO/technik01.htm

[11] EU Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC:
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1992L0042:20040221:DE:PDF

[12] BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) 2008: *Energie dreifach nutzen: Strom, Wärme und Klimaschutz: Ein Leitfaden für.... Mini-KWK*; (German only; translation: *Applying Energy Threefold: Electricity, Heat and Climate Protection: A Guide to… Mini-Co-Generation*) http://www.bmu.de/files/pdfs/allgemein/application/pdf/leitfaden_mini_kwk.pdf

[13] EEG: *Erneuerbare-Energien-Gesetz 2009* (German Renewable Energy Sources Act 2009), Bundesgesetzblatt (Federal Law Gazette) Vol. 2008 Part I No. 49, p. 2074 et.seq.
http://www.bgblportal.de/BGBL/bgbl1f/bgbl108s2074.pdf

[14] EU *Decision 2007/74/EC establishing harmonised efficiency reference values for separate production of electricity and heat in application of Directive 2004/8/EC*;
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:032:0183:0188:DE:PDF

II.4 Biomass power plants

4.1 Introduction

Historically, biomass stands for fuel at the beginning of purposeful energy generation by human beings and at the beginning of the utilisation of renewable energy sources. The utilisation of biomass – which nowadays generally denotes all plant and animal materials including waste products from metabolism – is climate-neutral in terms of CO_2 emissions but not with regard to other greenhouse gases (methane, laughing gas, SO_x, NO_x). Biomass has a share of about 70% of the renewable energy sources in Europe, with electricity and heat generation being the major applications.

The current and future utilisation of biomass for energy generation needs to be considered within a wider context of sustainability that includes, apart from sustainable land use in terms of agriculture, forestry and water management, the issues of competitive land use for energy crop agriculture or for food production from plants and animals and other uses as well as the issue of biodiversity. Therefore, in future, the use of biomass for energy generation needs to be discussed, if possible, in terms of planting otherwise non-cultivable land, new methods of producing biomass (e.g. from algae) and in particular the extended utilisation of residual biomass, be it silvicultural or agricultural (including liquid manure) or household waste (biomass and disposed organic products made from about 50% fossil feedstock). The new methods of transformation of ligneous biomass for the production of gaseous or liquid energy carriers are also referred to as second generation bioenergy[1] which is believed to be of importance after 2020.

4.2 Utilisation of biomass for energy generation

Germany has been a net import country for agricultural goods and food over the past decades despite an enormous growth in its agricultural productivity. In 2004, imports amounted to about 12 billion €, while the total value (at producer's price) of Germany's agricultural and silvicultural production was about 45 billion €. This equates to about one percent of the German national gross domestic product and an employment of about 2.2% of all earners. In Germany, 17 million ha – or 49.3% of the total area – are used for agriculture, 11.8 million ha of which are for plant production and 5 million ha as permanent grassland. About 10 million ha are used for food production, 275,000 ha for industrial crops (starch, sugar, technical rapeseed oil, etc.) and about 2 million ha for energy crops. Short rotation plantations (micanthus, willow, poplar), which are considered for energy use, so far play only a minor role at about 1,000 – 1,500 ha. Extrapolations assume a potentially available area of up to 4.74 million ha for bioenergy carriers in 2010 which could be increased to 7.23 million ha, or 42% of the overall agricultural area used, by 2020[2].

Biomass can be utilised by applying thermochemical, physicochemical, or biochemical processes, the selection of which is governed by aiming for the most efficient conversion into the desired energy carrier. During this process, biomass is converted into solid fuel (carbonisation), biogas (synthesis gas, lean gas), or liquid fuel (methanol, pyrolysis oil, PME, ethanol). These processes generate fuel, electricity or heat, the latter of which can also be achieved directly by biochemical aerobic degradation. In the long term,

---

1 Source: e.g. K. F. Ziegahn, Karlsruhe Institute of Technology, in "Welternährungslage und Bioenergie" (German only; translation: "World Food Situation and Bio Energy"), German Federal Chancellery workshop, 19 May 2008. (http://www.bmelv.de/cae/servlet/contentblob/380404/publicationFile/22140/BerichtWelternaehrung.pdf)

2 Source: D. Thrän et al.: *Nachhaltige Biomassenutzungsstrategien im europäischen Kontext* (German only; translation: *Strategies for a Sustainable Use of Biomass in the European Context*), final report by the BMU (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), 2005 http://www.bmu.de/erneuerbare_energien/downloads/doc/36715.php

gasification seems to be the most promising option for electricity generation due to the high conversion efficiencies achievable.

In 2007, about 200 biomass CHP plants, with a total installed nominal power of about 1.2 GW, including about 160 MW from power plants of the paper and pulp production industries, were in operation in order to generate electricity from *solid biomass*. Most of these facilities are small: power plants with a power of more than 5 MW only have a combined total nominal power of 400 MW. In addition to electricity generated from genuine biomass, about 4 TWh/a (about 450 MW) are generated from the combustion of household waste. About 2.7 TWh/a were generated from *liquid biomass*, however, some of the fuel was imported (particularly palm oil). The extension of biogas facilities, mostly in the agricultural sector, has led to an overall electricity generation of 7.5 TWh/a in 2007 and has been increasing considerably. In total, about 23.4 TWh/a (about 2.7 GW) of electricity was generated in 2007, which equates to about 3.1% of Germany's gross electricity generation[3].

Usually, electricity from biomass is co-generated with heat for local or district heating. Electricity generation takes place in these small power plants with modest efficiencies. When further extending power plants, they need to be capable of generating at least 20 MW_e (in order to achieve electrical efficiencies of 28-32% in the heat-controlled mode of power plant operation, see chapter II.3) or better yet, the co-fuelling of large scale power plants (with degrees of efficiency >45%) needs to be aimed at.

4.3 Potentials

Estimates of the present technological potential of biomass for energy generation in Germany are about 1,000-1,300 PJ/a, or about 8% of the current annual primary energy consumption[4]. Forestry and the specific cultivation of energy crops account for about a quarter each, the remainder comprises waste wood, industrial wood, straw and grass as well as agricultural biogas (mostly liquid manure), landfill gas and sewer gas. In Europe, the technological potential of biogas is estimated to be higher by a factor of 10 and by a factor of 100 worldwide[5]; the latter equates to about 30% of the current primary world energy consumption (2005: 407 EJ/a). However, projections differ significantly (see below). In the medium term (by 2020), Germany and Europe could achieve an increase by some 10%; in this regard, the increase in energy crop cultivation plays the most important role apart from specific yield increases and the utilisation of so far unused growth. It must be noted in this regard that only 7% of the biomass used for energy purposes (mostly residual materials) is being used for electricity generation in Germany.

The worldwide potential for increasing the production of biomass is assessed very differently at below 50 up to above 400 EJ/a for the year 2050 depending on the estimates[6], the decisive factor being the level of increase in energy crop cultivation. The potential of organic residual materials from agriculture and residential areas as well as downstream industrial sectors, however, is estimated to be significantly lower at 25-90 EJ/a[7]. When giving an estimate of energy crop cultivation, competitive land use for food production and other purposes plays an important role. Food demand and area productivity vary each year by a few

---

[3] Source: Kaltschmitt loc. cit. and http://www.thema-energie.de/energie-im-ueberblick/zahlen-daten-fakten/statistiken/energieerzeugung/bruttostromerzeugung-in-deutschland-2007.html

[4] See, e.g., Kaltschmitt et al. *Lifis online*, www.leibniz-institut.de, 25 April 2008

[5] M. Kaltschmitt, H. Hartmann: *Energie aus Biomasse* (German only; translation: *Energy from Biomass*), published by Springer, 2001

[6] Berndes, G., M. M. Hoogwijk, and R. van den Broek (2003): *The contribution of biomass in the future global energy system: a review of 17 studies.* In Biomass & Bioenergy, Vol. 25(1), p. 1-28. (NWS-E-2003-40), quoting D. Thrän et al. S. Gesemann et al. loc. cit.

[7] The WBGU (German Advisory Council on Global Change) estimates the technological potential of biogenic waste and residual materials to be 80 EJ/a worldwide, 50 EJ/a of which comply with the principles of sustainability, and again half of which is estimated to be economically realisable ("Zukunftsfähige Bioenergie"; German only; translation: "Sustainable Bio-Energy" (2008)).

percent and depend on the particular developmental scenario. Taking a scenario of "environment and health" as the basis which assumes, despite the growing world population, a stop of further deforestation; an ecological form of agriculture (i.e. decreased or constant area yield); as well as a decrease in the surplus food production in some western industrialised countries and an improvement in food supply in other countries (while at the same time assuming a significant reduction in cultivated land due to a change in dietary patterns including foregoing meat); it follows that for Asia, Africa and Central America there is no great energy crop potential. In comparison, the potential for North America (>17 EJ/a), Europe (~20 EJ/a; ~14 EJ/a of which for the EU-27), South America and Australia (7 EJ/a each) with a total of >50 EJ/a is significant[8]. Larger potentials can be realised by expanding the cultivated land (mainly by deforestation, possibly by using the arctic tundra). It remains to be seen whether an intensified utilisation of residual biomass and novel methods for biomass production, for example from algae, will lead to major changes. In the long-term (time frame 2050), a sustainable technological potential of about 80-170 EJ/a is considered possible, about half of which should be realisable in practice[9].

Medium-term (2020-2030) predictions for Europe assume 30-35 million ha of cultivated land for energy crops. The corresponding energy yield from biomass could amount to 6-7 EJ/a (Germany >1.3 EJ/a), equating to almost a doubling as compared to 2007. No significant increase is expected with regard to (residual) forest wood and residual materials. Energy crops, therefore, could contribute more than half of the total biomass potential in the future[10].

If all of the technological potential of biomass were utilised to provide final energy as electricity in Germany, about 100-130 TWh_{el}/a or 17-22% of the German gross electricity production (2009: 596 TWh) could be provided[11]. Whether this is worthwhile depends, apart from the assessment of competitive land use, mainly on whether biomass can replace fossil fuels with a larger overall efficiency in other processes for purposes of final energy utilisation. In fact, liquid fuel production and heat applications play a large role and will probably continue to do so. A doubling of electricity generation mainly from solid and gaseous biomass energy carriers to 48 TWh_{el}/a, requiring cultivated land of about 1.1 million ha in 2020, is considered likely as a "basis scenario"[12].

4.4 Competitive land use and ecological considerations

An examination of the competitive use of biomass is complex since various aspects (crop cultivation, processing, material or energetic use, by-products, substitution), geographical regions and economic interconnections (e.g. food, animal feed and wood markets as opposed to the fossil energy market) need to be considered[13]. This matter will not be discussed in this study. Furthermore, politically motivated price fixing

---

8 Seidenberger, T., Thrän, D., Offermann, R., Seyfert, U., Buchhorn, M., Zeddies, J., 2008: *Global Biomass Potentials – Investigation and assessment of data, Countryspecific energy crop Potentials, Remote sensing in biomass Potential research.* Final Report, DBFZ (Deutsches BiomasseForschungsZentrum; German Research Centre for Biomass). Commissioned by Greenpeace International. Citing D. Thrän et al., S. Gesemann loc. cit. being prepared for publication. The WBGU (German Advisory Council on Global Change) (loc. cit.) gives a margin of 30-120 EJ/a.

9 Source: WBGU (German Advisory Council on Global Change), loc. cit.

10 Source: D. Thrän et al.: *Nachhaltige Biomassenutzungsstrategien im europäischen Kontext* (German only; translation: *Strategies for a Sustainable Use of Biomass in the European Context*), final report by the BMU (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), 2005 http://www.bmu.de/erneuerbare_energien/downloads/doc/36715.php

11 Source: M. Kaltschmitt et al. "Zur energetischen Nutzung von Biomasse in Deutschland – Potenziale, Stand und Perspektiven" (German only; translation: „On the Use of Biomass in Germany – Potential, Status and Perspectives"), LIFIs Online (25 April 2008) www.leibniz-institut.de ISSM 1864-6972

12 Thrän, D. et al., Gesemann, S. et al. See footnote 13

13 D. Thrän et al., S. Gesemann et al. *Identifizierung strategischer Hemmnisse und Entwicklung von Lösungsansätzen zur Reduzierung der Nutzungskonkurrenzen beim weiteren Ausbau der energetischen Biomassenutzung, Zwischenbericht* (German only; translation: *Identifying Strategic Obstacles in the Further Expansion of the Use of Biomass*), Leipzig 2009

needs to be examined, which, in the form of tax reliefs or compensation for electricity from biomass fed into the grid, may distort the genuine market formation and market competition and favour energy crop cultivation rather than food production[14].

The competition between food and energy crop production worldwide has shifted more and more to the detriment of the former. The decade-long trend to lower real agricultural prices has been reversed. Particularly the tremendous expansion of fuel production from plants (to a lesser extent electricity generation from biomass) is considered to be the cause. Apart from that, other factors contributing to increasing food prices must not be ignored, such as the demands of the growing world population, increasing demands in regard to food supply (meat) with increasing prosperity, increasing energy prices, crop failures and speculation. More than a third of US grain production was used for the production of ethanol in 2006/7; in Europe, half of all vegetable oil was used for biodiesel production. (90% of the world production of bioethanol is concentrated equally in the US and Brazil, 75% of the production of biodiesel is concentrated in the EU). This competition between energy crop and food production has been made responsible for more than half of the worldwide increase in food prices of 140% total between 2002 and 2008[15,16]. Therefore, the social impact[17] of biomass growing and the environmental costs need to be examined as well. Primary goals must be: development of energy crops with higher specific yield and moderate demands for fertiliser, production of liquid fuels (ethanol, diesel) from cellulose of residual materials (straw, residual wood) and other improvements reducing competitive land use[18].

Specific criteria for the development of the utilisation of biomass are, amongst other things, energy gain, CO_2 avoidance costs, biodiversity, emissions harmful to health or the environment (particulate matter, NO_x, CO, PO_4, SO_2), soil and groundwater protection and alterations in the natural landscape. A notable example is the use of energy from grassland in Germany; in this regard, grass silage, combustion or dry fermentation of hay as well as poplar short rotation plantations and corn fields are a possibility[19]. Poplar short rotation plantations and corn fields are economical and useful for CO_2 avoidance, but there are drawbacks to them in other regards. Limited crop rotation of corn and rapeseed, for instance, which are the dominant crops in Germany at present, requires increased pest management measures. The four chemical agents that are being used are found amongst the ten worst water polluters. Application of fertilisers causes nitrate pollution of groundwater (in particular with regard to corn in connection with late sowing dates and low ground cover), however, the amount of fertilisers applied is less than that used for food crops and perennial energy crops can in addition have environmental advantages.

In Germany, energy crop growing has led to a significant recultivation of cultivable acreage that had previously been disused in accordance with EU regulations and this has had positive effects on agriculture

---

[14] This also applies to e.g. bio-diesel, for instance in the US: More than 200 supporting measures at an annual amount of 5.5–7.3 billion US$ equate to subsidising an equivalent liter of ethanol at 0.38-0.49 US$. See *World Bank: World Development Report 2008*, p. 70.

[15] World Bank: World Development Report 2008, chapter III. See also: Aditya Chakrabortty, guardian.co.uk, http://www.guardian.co.uk/environment/2008/jul/03/biofuels.renewableenergy).
This report states a price increase of 75% and thus disagrees with the marginal influence of energy crop production of merely 3% claimed by the US government. Caused mainly by the US ethanol programme, corn prices increased by 60% between 2005 and 2007 alone. Further, albeit less drastic, price increases are to be expected if the massive subsidisation of biofuel is continued.

[16] The production of 100 liters of ethanol requires 240 kg of grain. This equates to the annual food requirements of one adult. Source: World Bank, Agriculture for Development Policy Brief Nov. 2007, http://siteresources.worldbank.org/INTWDR2008/Resources/2795087-1191440805557/4249101-1191956789635/Brief_BiofuelPrmsRisk_web.pdf

[17] Most poor countries are net importers of grain and thus are especially adversely affected by rising prices.

[18] The demand for land is going to remain very high in the foreseeable future, however: 30% of the overall corn harvest can only provide 8% of US petrol consumption through ethanol production. (Source: World Bank, Policy Brief, loc. cit.)

[19] Stelzer et al. KIT (2007) http://www.itas.fzk.de/deu/lit/2007/stua07b.ppt. The potential cultivated land for short rotation plantations is estimated to be about 0.4-0.5 million ha. (A. Bemmann, TU Dresden, http://www.tll.de/ainfo/pdf/afs/afs14_09.pdf)

and the job market. However, it has also led to increasing lease and purchase prices for fertile agricultural land in some regions, although a certain balance could be achieved by an expansion of agricultural land use or an increase in land productivity. Biogas production has been established particularly in regions dominated by livestock breeding and can adversely affect the cost-effectiveness of cattle farming by limiting free range and by increased animal feed costs[20]. Biomass import might mitigate these problems as long as it does not cause similar problems in countries of origin (reduction in biodiversity, destruction of the rain forest (Brazil), loss of indigenous livelihood of farmers in developing countries, etc[21].

The effect on employment increases in parallel with the value creation in rural regions. Due to the lower volumetric energy density (particularly of residual materials, e.g. for straw 2 GJ/m^3), it is advisable anyway to process biosyncrude ("bio-crude oil", e.g. produced via pyrolysis, 25 GJ/m^3) locally, i.e. decentralised, and to centralise only the remaining process units of synthesis gas and fuel (diesel, 36 GJ/m^3) because of advantageous economies of scale.

In order to avoid competition for land use, the future production of chemical base materials and synthesis fuels on the basis of biogenic residual materials from food production is appealing since the amount of residual materials increases with growing food production. Pyrolysis and gasification to synthesis gas and subsequent processing into methanol as well as methanol production from waste wood (lignocellulosic ethanol) are of primary concern; however, other processes, too, such as biomass production from algae may play a role. In view of these developments, today's first generation processes may be considered bridging technologies.

4.5 Outlook

In summary it may be said that over the next 30-40 years biomass could contribute to energy supply 3 to 6 times the amount it does today, without additional expansion of cultivated land through deforestation. In the long term, utilisation of so far unused land could open up even greater potential (e.g. fallow areas in Siberia or Canada). Biomass, therefore, has an important part to play in the sustainable energy generation of the future.

Electricity generation from biomass has the advantage of being independent from fluctuations and thus being capable of providing base load. What kind of role it is going to play in Germany depends on the amount of land use expansion for energy crop growing and on its use for electricity generation. So far, fuel production generally has been the focus of political attention[22], electricity generation being a by-product at best, even though the replacement of electricity from coal with electricity from biomass is considered to be much more beneficial to climate protection than fuel production for traffic since first generation biofuels perform rather poorly in this regard[23]. In practice, the contribution of biomass to electricity generation will be able to reach

[20] Deutscher Bundestag (German Parliament), hearing about biomass / competition of resources: http://www.bundestag.de/presse/hib/2007_11/2007_291/03.html

[21] There have been many political declarations of intent regarding the protection of biological diversity in the past 20 years, particularly the *Convention on Biological Diversity* (1992) which provided the basis for the enactment by the German Cabinet of the German "Law Regarding the Convention on Biological Diversity" (Gesetz zum Übereinkommen über die biologische Vielfalt 30.08.1993, BGBl. II Nr. 32, p.1741-3) and the German "National Strategy for Biological Diversity" (*Nationale Strategie zur Biologischen Vielfalt*, November 2007).

[22] In shaping (or nullifying) market conditions or market support, significant shifts between different products (and their respective land use) can be achieved; this is demonstrated by the instantaneous decrease in pure biodiesel by more than 40% in the years 2007-2008 due to the change in taxation in Germany.

[23] Factsheet Bioenergie 1/2009 (German only; translation: Factsheet Bio-Energy 1/2009), Wissenschaftlicher Beirat der Bundesregierung – Globale Umweltveränderungen (German Advisory Council on Global Change)

perhaps about 10-15% of Germany's gross electricity production[24].

However, the sustainability of bioenergy use needs to be guaranteed by suitable national and international regulations. A considerable expansion and the economic-ecological optimisation of electricity generation from biomass require significant research and development, particularly in terms of the new types of biomass production and processing named above (residual biomass use, algae) which avoid competition with food supply safety, nature conservation and climate protection.

[24] "Basisszenario 2006" (German only; translation: "Basic Scenario 2006") (see e.g. J. Diekmann (co-ordinator) *Analyse und Bewertung der Wirkungen des EEG aus gesamtwirtschaftlicher Sicht* (German only; translation: *Analysis and Evaluation of the Effects of the German Renewable Energy Sources Act (EEG) From an Macroeconomic Point of View*), DIW (Deutsches Institut für Wirtschaftsforschung; German Institute for Economic Research) 2006, chapter 1, p. 29

II.5 Solar power generation

5.1 Introduction

Solar energy is the primary source of most renewable energy sources. It can be applied directly for electricity generation either by using the photovoltaic effect or utilising a thermal conversion process for which solar radiation is concentrated via mirrors onto receiving systems in which a liquid is heated that subsequently drives a turbine-coupled generator in a conventional steam cycle. This concentrated solar thermal electricity generation requires direct solar radiation. Global radiation is essential for photovoltaics, however – since it is for non-concentrating solar thermal systems which are useful for household and industrial water heating but are unsuitable for electricity generation due to the low temperatures achievable.

Global solar radiation[1] per square metre of the earth's surface is about 1 kW/m^2. Clouds, mist or fog cause considerably lower values – and the daily and seasonal fluctuation must be taken into account, of course. Germany's yearly average of solar radiation, therefore, is only[2] about 110 W/m^2. Depending on the site, Germany can expect an annual global amount of solar radiation of about 900 – 1,230 kWh/m^2/a (figures for 2008). Cloudless skies are not common in Germany. They most rarely occur over the German low mountain ranges of North Rhine-Westphalia and most frequently over the upper Rhine valley near Freiburg as well as over the foothills of the Alps. On average, the number of hours with a high amount of *direct* solar radiation is about 1,550 hours a year, i.e. only about 18% of the total annual number of hours.

Expediently, solar plants for electricity generation should be built where there are optimum irradiation conditions, i.e. in the "sun belt", that is in the southern European countries and northern Africa and, going beyond areas of interest to Europe, also in large areas of Australia, the Americas, and Asia. Compared to Germany, the amount of irradiated annual solar energy in, for example, southern Spain or Italy can be twice as high; and, at >2,300 kWh/m^2/a, it is higher by up to a factor of 2.5 in suitable regions of northern Africa than at many German sites. Accordingly, the required specific module and absorber areas and thus the land requirements and investment costs are lower. Furthermore at southern sites, in as far as the use of roof areas is not possible, the shading of the land by modules or collectors may pose less competition to other forms of utilisation, in particular agricultural use, but, instead, may even support them.

Compared to Germany the share of direct radiation is much higher in the sun belt, and electricity generation via concentrated solar power is here the obvious method. Thus, for solar power there is a considerable competitive advantage for southern regions over northern sites even though common photovoltaic cells have a lower degree of efficiency due to the oftentimes high temperatures at these southern sites, i.e. the electricity yield does not increase linearly with the available radiation.

These scientific facts imply that electricity generation should not be considered predominantly under the aspect of self-sufficiency on German territory. Rather, it could be a desirable political goal to secure for German research a leading position in order to acquire and suitably expand for German industries the largest possible share in the development and utilisation of the *worldwide* potential of solar power generation. That way, much greater benefits could be gained both for climate protection and the German economy than by building solar power systems in sun-deprived Germany.

---

[1] This is the standard value for the atmospheric mass index AM 1.5, i.e. 41.8° solar altitude. Not only the radiant power but also the spectral distribution varies according to the angle of incidence.

[2] Source: Deutscher Wetterdienst (German Meteorological Service)

5.2 Electricity generation using photovoltaics

The photovoltaic effect was discovered in 1839, the first photo-electric cell from selenium was built in 1883 and the first solar cell in 1893. It was only some sixty years later that the production of high-purity silicon became possible which was the basis for the production of solar cells with various practical uses. Another 55 years later, a notable sector of industry developed in Germany, and increasingly worldwide, whose existence, however, still continues to depend mainly on the immense (German) subsidisation of photovoltaics.

5.2–a General aspects and market development

Amongst all renewable energy sources with regard to grid-connected electricity generation, photovoltaics (PV) still is, by far, furthest from being economically competitive. The most important goal, therefore, is to decrease the costs as quickly and effectively as possible and reach true competitiveness.

The currently common systems require at least 7 m^2 of module surface in order to reach a peak performance of about 1 kW. At present, roof-mounted systems dominate in Germany. The theoretically suited roof area is estimated to be ~1,300 km^2 in Germany[3]. However, some part of it is not useable due to unfavourable conditions or inclination (or only useable after complex substructures have been built), or is not optimal due to shading, or – particularly with regard to residential buildings – could preferably be used for solar hot water generation instead of photovoltaics. To the roof areas, 600 km^2 of building façade can be added. Thus, the maximum potential of the photovoltaic electricity generation on German buildings may be about 10 GW effective power averaged over the year[4] – the power higher in summer and considerably lower in winter.

Despite the unfavourable solar irradiation conditions in Germany, nearly half of the worldwide power increase in 2007 was installed there[5]. This development is continuing at breakneck speed: the installed power increased from 3.8 GW_{peak} (or ~ 380 $MW_{annual\ average}$) at the beginning of 2007 to 5.3 GW_{peak}[6] (or ~ 530 $MW_{annual\ average}$) a year later. For large-scale power production solar facilities in open spaces are going to play a more significant role – particularly in the regions of the world's sun belt. In Spain and Italy, much less power was installed despite much better radiation conditions[7]: at 3.4 GW_{peak} and 0.3 GW_{peak}, respectively these countries at least are, after Germany, the next largest PV sites in the EU where the overall increase in installed power was 1.8 GW_{peak} in 2007 and is estimated to be 4.6 GW_{peak} in 2008[7]. In Germany, the most

---

[3] NEEDS RS1a – WP11, 2005 2005 Final report on technical data, costs and life cycle inverntories of PV applications, P. Frankl et al., Report to the European Commission, p.10. Citing: http://www.needs-project.org/docs/results/RS1a/RS1a%20D11.2%20Final%20report%20on%20PV%20technology.pdf.
An estimate by EcoFys (www.solarserver.de/news/news-7381.html) states 1,760 km^2 but includes all areas which have inclinations to the geographical south up to 45%. The effective area therefore is similar to the one given by NEEDS. Hoffschmidt et al. give installable powers (roof) of 95.5 GW_{peak} which equates to about 10 GW averaged over a year ("Struktur und Dynamik einer Stromversorgung mit einem hohen Anteil erneuerbarer Energieerzeuger – Energiestudie"; German only; translation: "Structure and Dynamics of a Form of Electricity Supply with a High Percentage of Renewable Energy Generators – Energy Study") intermediate report 2009, p. 22.

[4] This equates to about 100 GW nominal power. Cf. the discussion on the following page and footnote 10.

[5] Source: Forschungsverbund Erneuerbare Energien (Renewable Energy Research Association).

[6] Source: *Le journal du photovoltaïque 1* (2009) p. 78. Figures for 2008 are estimates. The percentage of off-grid PV decreased from 9% (2007) to 7.5% (2008).

[7] The main part of PV installations shifted to Spain in 2008 when a feed-in compensation following Germany's example was adopted there which resulted in a total installed power of about 3.4 GW_{peak}. After a cap on feed-in compensation had been imposed and the tariff had been lowered by about 30%, investments decreased considerably.

recent figures suggest a continuing rapid increase in new installations (3 GW_{peak}[8]).

In order to harness the potential of this rapid growth, production capacities are being increased worldwide. In 2005, they amounted to about 1,900 MW/a and will probably reach 14,000 MW/a in 2010, of which only about 20-25% will still be located in Europe[9]. If the plans announced by the industry were implemented entirely, production capacities would increase to 35,000 MW/a. In the meantime, production lines are designed to operate at several hundred MW/a. The photovoltaics industry has become a buyer of silicon comparable to the general electronics industry and could soon become the largest one if no change in technology takes place. Particularly the industry in Asia, with a rapidly increasing share of Chinese companies, has taken the leading role in module and cell production – Germany, however, still remains the most important market due to the high return on investment achievable owing to subsidies based on the German Renewable Energy Sources Act (EEG).

The use of the peak performance of photovoltaic plants as the nominal power easily leads to misunderstandings[10] with regard to practical assessments. The actual amount of generated energy (2007: 4 TWh) equates to an annual average power of only 10% of the nominal power[11], whereas the annual average power of conventional thermal base-load power plants is above 90% of the nominal power and on-shore wind power at least reaches 20-25%. Specifically, in Germany photovoltaics provided an average power of merely 456 MW from an installed nominal power of 4,550 MW in 2007[12].

There are two reasons for the low average power of photovoltaics. First, photovoltaics does not generate electricity at night and only little in the mornings or evenings which is why the daily production curve deviates considerably from demand. Furthermore, the seasonal conditions are rather unfavourable in Germany: there is much radiation in summer (global radiation in July is 135-180 kWh/m^2), in winter, however, when there is higher demand, electricity generation virtually stops (global radiation in January is 10-30 kWh/m^2, figures above 30 kWh/m^2 are reached only in the foothills region of the Alps and more than 40 kWh/m^2 exclusively in higher regions of the Alps[13]). For this reason the electricity demand during the night, morning and evening as well as most of the electricity demand during winter needs to be supplied consistently by other power plants.

Investing in photovoltaics as an essential part of German electricity generation necessarily requires investments in other power plants with a generating capacity of virtually the same order of magnitude. In other words: photovoltaics generally cannot replace other power plants (even considering the required investment) but only that share of electric power that is generated there which is equivalent to the photovoltaic power. This reduces the required amount of fuel in fossil-based, nuclear or biomass power plants; however, when fuel savings are calculated, it must be taken into account that thermal power plants are operated in order to supplement the fluctuating electricity generation i.e. partially in low load or part load regimes for which the efficiencies are lower than in full load regime. Therefore, when making an economic assessment, just as when assessing other fluctuating electricity sources (such as wind power), the necessary auxiliary costs need to be considered at all times, i.e. the necessary capital expenditure for

---

8 Source: Spiegel-Online (German online newspaper), 9 February 2010

9 Source: PV Status Report 2008, Joint Research Centre, European Commission.

10 It was postulated by the German newspaper TAZ on 5 August 2009 that the installed photovoltaic power of 2.7 GW equated to two large German nuclear power plants. Actually, however, photovoltaic plants with up to 27 GW nominal power would need to be built as well as additional nuclear, coal-fuelled or other power plants with nearly 2.7 GW power in order to replace two nuclear power plants in Germany.

11 Regarding the consequences of back-up power plants and requirements for grid extension see chapter III.1.

12 Installed power based on the annual average.

13 Source: Deutscher Wetterdienst (German Meteorological Service), *Mittlere Monatssummen für den Zeitraum 1981-2000*. (German only; translation: *Monthly Averages for 1981-2000*). The direct radiant power varies even more during the year.

controllable standby or backup systems (or the costs of electricity storage units, should they exist eventually[14] and the apportioned operating costs need to be added to the actual costs of the photovoltaic systems. Photovoltaics, therefore, can only play an important and useful role with regard to future large-scale electricity supply, if much more cost-efficient systems are achievable through further intensified research and development.

Electricity generation from photovoltaics has undergone a steady technological development alongside with an *increase in productivity* – however, estimates for 2015 still predict electricity costs of 20-24 c per kWh in Germany[15] in which the backup costs mentioned above are not even included. It is often stated that with this photovoltaics would have achieved so-called “grid parity” where the costs would equate to the household electricity costs of domestic customers[16]. This view ignores the fact that the latter cost comprises operating, grid and infrastructure costs including duties and taxes at currently about 14-18 c and thus the argument is not useful for an assessment of cost-effectiveness. Grid parity is not even a suitable category if a grid connection is forgone completely as costs for decentralised storage or backup generators including the required fuel and a comparable tax and duty burden need to be added to the photovoltaics costs.

In southern Europe electricity from photovoltaics can be generated at half the costs incurred in Germany (perhaps even more economically as the costs for sites may be lower) due to higher solar irradiation and its more balanced seasonal fluctuation. Transportation of PV-generated electricity from these regions to Germany may be considerably more advantageous with regard to both cost-effectiveness and climate protection than electricity generation from domestic PV installations. It should be examined whether electricity from German photovoltaics can be competitive, despite the basic disadvantage of location (due to unfavourable radiation conditions), in a future entirely deregulated single European electricity market in which electricity providers from various regions compete with each other.

Photovoltaics is a suitable technology for those cases of moderate electricity demand where a grid connection is not available. This applies to many mobile applications as well as immobile demand where the costs of a grid connection are comparable to or higher than the capital costs of a photovoltaic system with electricity storage unit. However, this off-grid area of application is comparably low in volume and the environmental balance, as long as the currently prevailing lead batteries are being used, is adversely affected by the oftentimes required storing of energy.

5.2–b Technological aspects

Crystalline silicon cells (mono-crystalline, multi-crystalline) still dominate the market with a share of more than 90%. Multi-crystalline cells are used predominantly. In case of mono-crystalline systems, Si bars are extracted using the Czrochalski method and sawn into wafers. During this process, half of the high-purity silicon is lost as saw dust[17]; also general sawing and breakage waste accumulates. In case of multi-crystalline cells, *direct* (or *directional*) *solidification* processes are used. Recently, ribbon methods have been

[14] Electricity storage units of the required order of magnitude and for time spans up to half a year are not in sight. See chapter III.2 of this study.

[15] Source: FVS (Forschungsverbund Sonnenenergie; Research Association Solar Energy), *Forschungsziele 2009* (German only; translation: *Research Goals*), p.6. No price is given for 2015 there but grid parity is mentioned which is to be read as 20-24 c/kWh. In its latest analysis (IEA/PRESS (10)04, Valencia, 11 May 2010), the IEA assumes grid parity in many regions in 2020 for PV systems (particularly in areas with favourable radiation conditions).

[16] The total costs for domestic customers per kWh (about 19.35 c) is made up of 11.8 c for electricity generation, transport and sale (2-6 c of which is spent on generation), 2.7 c sales tax, 0.75 c for EEG, 0.3 c on CHP (combined Heat and Power levy), 2 c electricity tax and 1.8 c concession levy).

[17] Wagenmann, H.-G., Eschrich, H.: Photovoltaik (German only; translation: Photovoltaics). Teubner, Wiesbaden (2007)

used where Si ribbons are extracted from the melt. Using these techniques much less (sawing) waste is created.

The increase in photovoltaic efficiency is an often cited parameter for the characterisation of the development towards an increased economic efficiency since area related costs such as land, material, installation etc. decrease with increasing photovoltaic efficiency of the modules which is typically about 14% to 17% for mass produced mono-crystalline cells, nowadays also for poly-crystalline cells, which equates to cell efficiencies of 16% to 19%.

Due to the foreseeable physical limits a decisive breakthrough towards cost-effectiveness will not be achieved by increasing cell efficiency alone.

The silicon requirements account for about half of the module costs and about a quarter of current system costs[18]. The usual thickness of silicon wafers is still about 180 µm – this is mainly due to mechanical and not optical or electronic necessities: about 100 µm are sufficient in this regard and, using special techniques, 10-20 µm may be possible.

Application-oriented research and development of Si systems is being pursued in many areas and promises a multitude of further gradual improvements. But the development of systems using thick semi-conductor layers (50-200 µm) of the “first technology generation” towards the manufacturing costs that could enable PV to compete with other CO_2-lean methods of electricity generation is not yet within sight[19]. The silicon requirements need to be decreased drastically or silicon needs to be replaced with materials which, in relation to the achievable amount of electricity, can be produced and processed much more economically and, in particular, also allow for more favourable overall system costs. In any case, major advances in technology are required to achieve these essential *large* cost reductions – and these advances can only be achieved in connection with drastically intensified research and development which also include basic aspects.

Thin layer technologies are increasingly applied. Here active cell regions are made of homogenous semi-conductor material which is deposited on separate substrates. Developments on Si basis (amorphous Si on glass or metal substrate) and with direct band gap materials are being pursued which have a considerably higher light absorption and thus can be thinner. In this regard, different variants of copper-indium-selenide cells (CIS) with layer thickness of a few micrometers or cadmium telluride cells (CdTe) must be mentioned. They are produced by vacuum evaporation or plasma deposition technologies onto different substrates. These cells require much less semi-conductor material and thus their production is characterised by a significantly lower energy input. Thin film systems promise more advantageous economic and also, to some extent, technical properties (amongst other things, easier integration of the modules into the outer roof skin when roof-mounted). However, they (still) have slightly lower efficiencies[20] even though their development already began a few years after that of the standard Si technology, and, furthermore, they imply particular risks to some extent due to the materials used[21].

These thin film cells, at times termed *“second technology generation”* (thin crystalline silicon systems of the future can also be subsumed into that term), achieved market introduction nearly a decade ago. Currently their market share is at about 10% with a growth rate of 80% per year (2007). The growth of mono- and poly-

---

[18] Source: Kaminiski, J. *Electr. Spectr. 150* (2006), 105-135.

[19] The financial crisis of 2009 made prices drop drastically – which, to this extent, will probably remain a temporary phenomenon.

[20] The currently highest efficiency of manufactured cells is at 15.4% (Global Solar Energy, Tucson, Sept. 2009)

[21] Cadmium (CdTe cells) is the main cause of concern.

crystalline Si cells, however, is at about 50% per year, based on a ten times larger market volume. A world market share for thin film cells of 25-30% is considered likely for 2010[22.]

Meanwhile, the costs of thin film cells have reached or fallen below the value of 1$/$W_{peak}$[23]. The primary goals of future developments generally need to be: focusing on non-harmful, recyclable materials, achieving an even lower energy input for cells and modules, and reducing the costs of the entire production chain in order to pave the way for economically more competitive systems.

The developmental potential of photovoltaic cells is by far not exhausted by the mentioned cell types. The use of optical concentrators for specific types of solar cells[24], stacked solar cells, band gap adapted cells[25] for increasing efficiency, nano-crystalline (silicon) film technologies, mesoscopic multi-phase systems etc. provide perspectives towards the *"third technology generation"*[26] which should also lead to the possibility of higher cost-effectiveness and greater flexibility when designing modules. Beyond the actual development of cells, technologies for module and system production as well as aspects of the life cycle (life time and ageing behaviour, disposal engineering and costs, etc.) remain important fields of research and development in order to make these advanced systems ready for marketing.

Another innovative field of research comprises two physically different groups, dye and organic solar cells, which are considered to be part of the second technology generation. Dye-sensitised cells do not belong to semi-conductor based systems but work electro-chemically, e.g. with an electrolyte[27] whereas organic solar cells utilise polymere, C60, pentacene, thiophene or other semi-conducting materials. These materials have a high light absorption and their currently still relatively low efficiency increases with rising working temperatures – contrary to most anorganic cells used so far. This may make them appealing for southern, sun-intensive sites.

These organic materials also feature specific problems, however, such as designing suitable doping with low susceptibility to diffusion or also, in some cases, an inherent UV sensitivity. In comparison with anorganic cells there are, generally, remarkable possibilities of organic material design and optimisation. It is necessary in this regard, however, to fully comprehend and model the physical mechanisms of these different systems.
Intensified basic research and development is required. Test set-ups show that life times of one decade or more can be reached today – which could open a possibility to reach usage times of about 20-30 years that are required in practice. However, the efficiencies of about 6 percent for areas of organic cells relevant for production and laboratory values of about ten percent for dye cells reached so far are comparatively modest.

The recent successes of nanotechnology have resulted in entirely new ideas finding their way into the innovative development of photovoltaics; testing them presents great scientific and technological challenges,

---

[22] China, for instance, has commissioned the largest solar farm in the world with a nominal power of 330 MW which is equipped with thin film cell technology (FirstSolar).

[23] Press release, FirstSolar, 4th Quarter 2008.

[24] These developments aimed at application in aeronautics have reached efficiencies of about 28% with crystalline Si or GaAs.

[25] Efficiencies above 30% (up to 39%) have been reached in these laboratory multi-junction cells. These values already approach the theoretically possible limit of efficiency. It is significantly lower than the thermodynamical limit as only one electron hole pair is created per light quantum and the remaining photon energy is converted into lattice vibrations (heat) which cannot be utilised. The "third technology generation" attempts, amongst other things, to go beyond this limit.

[26] M.A. Green: *Third Generation Photovoltaics*, Springer Verlag, Berlin (2003). The term "third generation" is used more loosely here than Green does.

[27] See "Graetzel cell" named after its inventor. Apart from that there are also systems with solid-state hole conductors (e.g. spiro-MeOTAD) or ionic liquids.

however[28]. Layers for cell design deposited from either the liquid phase or in vacuum allow for the utilisation of cost-effective large-scale role-to-role methods and the use of a multitude of substrates (including flexible ones). All in all, possibilities of cost-effective, light-weight and flexibly applicable systems are opening up owing to inexpensive materials, lesser mechanical sensitivity and a production method closely related to established mass printing methods.

Although many scientific and technological obstacles still need to be removed, these new concepts provide basically interesting possibilities of comparatively low costs. These developments, therefore, as well as those of anorganic systems ought to be advanced, also because a broad spectrum of applications of organic electronics apart from photovoltaic applications is emerging.

5.2–c Sustainability balance

An important issue is the environmental and sustainability balance of energy systems, i.e. the issue of pollutants, hazards and energy input into production and application. The photovoltaic systems used so far have an unfavourable climate and sustainability balance in comparison with the emerging photovoltaic concepts but also with other renewable energy sources, as the production of crystalline silicon wafers requires much energy for current thick film solar cells. In 2010 the accumulated emissions from PV systems were estimated to be about 90 mg SO_2 and 100 mg NO_x and 50 g CO_2 per kWh[29]. CO_2 emissions per kWh are significantly higher, therefore, than those of other renewable energy sources[30]. The energy payback time is about three years for current multi-crystalline Si systems in Germany and comparable countries, and for thin film systems about 1.5 years[31]. Of course, the sustainability balance in southern regions is much more favourable due to their higher electricity yield than that in Germany with its low solar radiation.

Generally speaking, material input is the most important factor in the energy balance. Thin film technologies provide an advantage in this context; the same applies to new approaches towards significantly thinner Si cells. Compared with those technologies, dye and organic systems should be able to have excellent values and environmentally friendly properties. However, apart from the cells and modules the other components of the system need to be considered as well; in so doing the gain from the much more favourable cell properties is levelled in the total balance. All in all, however, these new technologies open up possibilities of considerably better sustainability balances.

5.2–d Leading position by intensified research and development

Research and development are the keys to an economically sensible and accelerated progress towards more cost-efficient and environmentally friendly photovoltaic systems. It is surprising, therefore, that the intensity of research and development in the photovoltaics industry has decreased from 2% to less than

[28] Cf. M. Riede et al. *Nanotechnolgy 19, 1* (2008)

[29] C. Kruck, L. Eltrop: *Perspektiven der Stromerzeugung aus Solar- und Windenergienutzung für eine nachhaltige Energieversorgung in Deutschland* (German only; translation: *Potential of Electricity Generation from Solar and Wind Energy Utilisation for a Sustainable Energy Supply in Germany*) FKZ A204/04 final report, IER (Institut für Energiewirtschat und Rationelle Energieanwendung; Institute for Energy Economics and Rational Application of Energy), Stuttgart, 2007. Jungbluth et al [30] state 84 g CO_2/kWh for the German electricity and PV system mix. In 2005, PV emissions of CO_2 still were at about 40%, of SO_2 500% and of NOx 70% of those of current natural gas and CCGT power plants (source: A. Voss, IER Stuttgart).

[30] Loc. cit. N. Jungbluth, M. Tuchschmidt, M. Scholten-de Wild: *Life Cycle Assessment of Photovoltaics: Update of ecoinvent data* v2.0, www.esu-services.ch (2008).

[31] Energy payback time is the time period by which the plant has yielded that amount of energy that was needed for production. Alsema (ECN Utrecht, 2006) gives energy payback time of about 5, 3.5 and 3 years for mono-crystalline, poly-crystalline, and ribbon systems respectively. Swiss Solar states 5.6 years for Switzerland, citing a study of the ETH Zürich and PSI Villigen. Thin film systems can reach 0.8 years in southern Europe and 1.5 years in Germany.

1.5% of its turnover despite the massive subsidisation of the market via the German Renewable Energy Sources Act (EEG)[32]. These (modest) R&D activities focus mainly on production-related aspects. For comparison: The big pharmaceutical companies have a research intensity of 15-20%, Microsoft 13.8%, Nokia 11.8% and Intel 15.2%[33]. Public funding of research is modest compared with the 2.8 billion € market subsidisation of photovoltaics alone via the EEG in 2008. R&D expenditure by the German government was only 322.8 million € for the entirety of non-nuclear energy research[34].

Often a historical *learning curve* is quoted demonstrating that solar power becomes more inexpensive by a factor of 2 every 7-10 years[35]. Thus, another 28-40 years and an expansion of the market volume by x numbers of times would be needed to make photovoltaics competitive. The electricity feed-in tariff for those 0.6%, which photovoltaics contributed to the gross electricity generation in 2008, equated to about 8% of the total costs of electricity generation[36]. The feed-in compensation guaranteed for 20 years already amounted, as per the EEG, to about 30 billion € for those facilities alone that were in operation at the end of 2008[37]. Due to the continuously and exponentially growing market expected by the industry, the compensation will increase manifold if the feed-in compensations are not reduced more drastically than planned or the volumes are not capped. The *increase in productivity* – an essential motivation for the German Renewable Energy Sources Act (EEG) – will probably not be valid in the future as technological development is increasingly reaching the limits imposed by the laws of physics[38], that is, new ways must be found. For this reason, research and development must be intensified in order to make leaps in technology possible – ideas, as mentioned before, exist.

Also for other reasons it is worthwile to consider whether the German market subsidisation via the German Renewable Energy Sources Act (EEG) serves its economical purpose since exports of solar cells are now being surpassed considerably by imports in Germany. None of the leading companies in the increasingly dominant market of thin film technology is based in Germany or Europe. Only the German supply industry, which has a small share of the sales volume of the PV-market, is booming due to the number of commissions for constructing PV factories worldwide, particularly in Asia. The largest and most appealing market by far for these new factories so far has been the German one financed via the German Renewable Energy Sources Act (EEG), however, there is now a growing world market as well[39]. A strong position for

---

[32] BSW Faktenblatt 2009 (German only; translation: fact sheet by the Bundesverband für Solarwirtschaft, the German Solar Industry Association), data for 2008; also cf. company report SolarWorld 2008 and European Commission, COM (2009) 519 final. The BMU (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), see IDW 18 November 2008, states 150 million € by the industry for R&D of photovoltaics and 40 million € by the BMU.

[33] Source: Booz&Co. Citing German newspaper FAZ (Frankfurter Allgemeine Zeitung), 29 October 2009

[34] Bundesbericht Forschung und Innovation 2008 (German only; translation: Federal Report Research and Innovation 2008), also see IDW 18 November 2008, Forschungsverbund Sonnenenergie (Renewable Energy Research Association)

[35] E. Weber (FHG), citing IDW – ForschungsVerbundSonnenenergie 18.11.2008, 11:23 news 289271

[36] The German gross electricity generation was about 617 billion kWh in 2008, equating to a turnover of about 36 billion €. 0.6% of the overall electricity volume was generated using photovoltaics. Compensations as per the German Renewable Energy Sources Act (EEG) were 2.8 billion € for that year alone.

[37] The issue of rampant costs was first pointed out by F. Vahrenholt (Repower, today: RWE Inngy), see e.g. German newspaper DIE WELT, 7 February 2009. The situation continues: The costs of the newly installed PV systems in Germany in 2009 alone (with an average annual power of about 300 MW, equating to 3 GW peak) were 14 billion € which are to be borne by the German customers due to the German Renewable Energy Sources Act (EEG)
(source: SpiegelOnline, http://www.spiegel.de/wirtschaft/unternehmen/0,1518,684477,00.html).

[38] The increase in photovoltaic productivity usually shows cost reductions of 20% for each doubling of the market volume although only 10% are given at times (see, for example, Gladwell, M. The Tipping Point, Little, Brown&Co., New York 2000). However, the possible performance gain for example in relation to the black body limit for Si cells has fallen below 20% and the physics and technology of Si cells is well understood today. Furthermore, there are concerns that the demanded massive PV expansion could possibly be endangered without a leap in technology because available feedstocks such as silver may be depleted (source: PV status Report 2008, JRC, European Commission, 2009).

[39] Plans have been announced by China and India for extending PV installations to double digit GW ranges in the upcoming decade. A similarly large market is expected for the US. These countries have large areas with significantly better irradiation conditions than Germany.

Germany in the export market (not just with regard to the supply industry) can only be extended in the long term by innovative, cost-effective photovoltaic systems.

In order to maintain a leading position it is necessary to notably intensify public research and development with regard to both a strongly accelerated development of silicon-based concepts and the rapid development of new approaches to (amorphous and crystalline) thin film cells as well as dye and organic photovoltaics.

Intensifying public research must be combined, however, with an increase in R&D expenditure by the photovoltaics industry to a (ten times higher) level which is comparable with that of other innovative industrial branches. However, the instrument of the German Renewable Energy Sources Act (EEG) has proven to be no incentive in this regard.

5.3 Concentrated solar thermal electricity generation

High-temperature solar power plants (concentrated solar heat, CSP[40]) that focus solar radiation onto absorber elements using large-area mirrors can utilise a high percentage of incident and then reflected solar radiation for heating a medium (e.g. air or water steam) to 500-1,000°C depending on the design. High temperatures are the deciding factor for the overall efficiency of electricity generation. As opposed to current large-scale photovoltaics, CSP systems can achieve an overall areal efficiency higher by about 50%, i.e. only two thirds of the sunlit area is needed in order to generate the same amount of electric power.

Due to its comparatively low direct solar radiation Germany does not have favourable conditions for concentrated solar thermal heat. As a basic principle, sites of low latitudes need to be used – that is, e.g. the sun belt of northern Africa or southern Europe. In northern Africa, at 32° northern latitude there is about 2500 kWh/m2 of direct (normal) annual radiation available and at 23° nearly 3,000 kWh/m^2 verfügbar[41]. A power plant having an area of 1 km^2 and an effective reflecting surface of 50% could generate about 90 MW annual average power in northern Africa. Pilot projects are in the pipeline and it is conceivable that large solar farms may be built if the expected properties can be demonstrated[42]. Compared to Germany and also to some parts of southern Europe the considerably more balanced seasonal fluctuation of solar radiation is important since it allows for a stable year-round availability of solar farms with high power (see Fig. 1).

The sunny regions of southern Europe and particularly northern Africa above 32° latitude are most interesting to Europe due to their short distance. There, solar power can be generated on a large scale and no great adverse ecological effects are to be expected. Also, competitive land use does not yield similarly good returns. There are many further appealing areas all over the world suitable for CSP, amongst them the Middle East, parts of China and India, Australia and the desert regions of the southern US. CSP will be able to provide a significant share of the electricity supply for the mentioned sites in the future. CSP, therefore, is an extremely promising field for the German industry which is currently the market leader.

---

[40] Concentrating Solar Power

[41] Source: Satelight and DLR: *Concentrating Solar Power for the Mediterranean Region (MEDCSP)*. Study commissioned by the BMU (German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Stuttgart, 2005.

[42] Cf. the DESERTEC and ESTELA initiatives

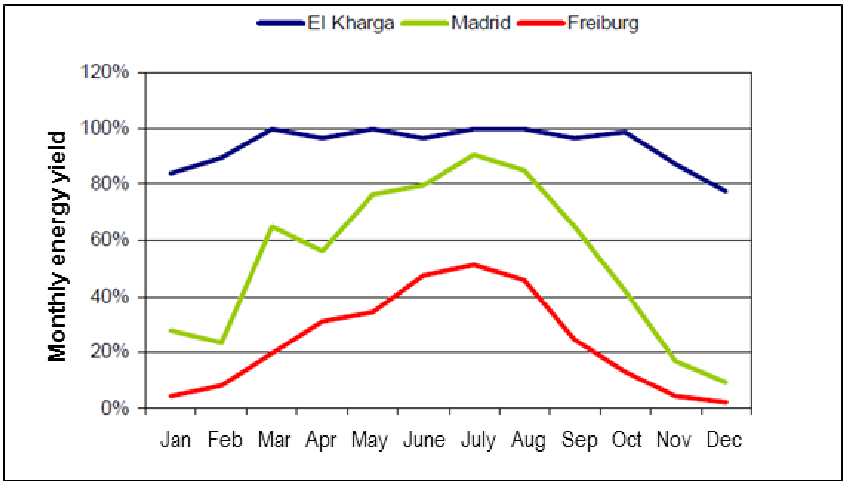


Fig. 1: Seasonal fluctuation of solar energy yields at three different sites. This chart clearly shows the advantage of north African sites ("El Kharga") with regard to a balanced seasonal fluctuation (source: Meteonorm 2005, cited by Nadine May, TU Braunschweig, 2005)

Furthermore, CSP at southern latitudes can play a significant role for the German (and even more so for the European) electricity supply in the long term. On the technical side, apart from solving many problems with regard to the power plant itself, a suitable transmission grid running from the generating regions in southern Europe and northern Africa to Germany is required. Conventional three-phase grids are not an option for the transmission of electric energy over long distances due to their high losses; instead, high-voltage direct current (HVDC) transmission must be used. For about 3,000-4,000 km cable length[43] to Germany, 20% losses need to be included in the calculation[44] and investments of about 300-500 €/kW (equating to about 10% of the power plant investment costs) need to be made[45].

When comparing solar heat to other forms of generating electric energy, e.g. geothermal energy, (clean) fossil-based power plants or nuclear energy, it needs to be taken into account that solar heat requires heat storage in order to provide an adjustable day-night power according to demand. Solutions for storage systems of the required size have been proposed[46], but there is no experience yet to allow an assessment of their potential in practice. A key point is that it is not electricity which is stored for hours but heat (up to 15 hours maximum to tide over the night). The storage systems currently being examined are unsuited for storing the accumulating heat volumes for a longer period of time. As an alternative (or addition) to heat storage solar heat opens up the appealing possibility, in some cases of application, to adjust the power in the power plant via co-firing (of fossil fuels or biomass) according to demand regardless of the solar irradiation pattern[47].

[43] A length of 3,117 km is projected for the Aachen-Algeria cables, 18 km of which as submarine power cables at the Strait of Gibraltar. The line from (southern) Libanon to Milan amounts to 3,108 km, 373 km of which as submarine power cables. (Citing N. May, *Ökobilanz eines Solarstromtransfers von Nordafrika nach Europa* (German only; translation: *Ecological Balance of Transferring Electricity from Solar Power from Northern Africa to Europe*), Institut für Geoökologie (Institute of Geoecology), TU Braunschweig, 2005)

[44] The losses of a double-bipolar line are stated to be 2.5-3.7% per 1,000 km at 800 kV (source: May, TU Braunschweig, loc. cit.). In addition to low current-independent losses, there are DC and AC rectifier and inverter losses.

[45] The costs are about 300-500 million € per 1,000 km plus costs of 350 million € per station for 5 GW transmission power. (Citing N. May, loc. cit.)

[46] Molten salt and other phase transition media as well as simple, inexpensive storage units from concrete or fill material (gravel) are some of the systems currently being tested.

[47] Neither of the two possibilities are an option for photovoltaics – storage units for electricity are not available at the required volume for the foreseeable future or have high losses; also, entirely separate additional fossil-based or biomass-fuelled power plants would be needed instead of using co-firing.

Several technological solutions are available for solar reflectors of CSP. Most often parabolic trough systems have been used which concentrate radiation onto, and heating up, a pipe, positioned in the focal line of the trough filled with an oil-based thermal fluid. Apart from geometric precision of the parabolic trough and its stiffness against torsion induced by wind load and tracking of the reflector system, vacuum isolation and selective coating of the pipe is important in order to reach temperatures above 200° and thus sufficiently high – albeit moderate when compared to fossil-based large power plants – thermodynamic efficiency. The most extensive practical experience by far has been gained from this type of solar thermal electricity generation[48]. Currently, the chemical stability of heat transfer oils limits the useful temperature to below 350° – 400°C[49]. Water as a heat transfer medium within the primary circuit allows higher temperatures and thermodynamic efficiencies to be reached. Successful testing of parabolic troughs has been done with direct evaporation as well – however, so far only up to 400°C feed temperature[50].

As an alternative to the difficult-to-build reflectors of parabolic troughs, owing to their size and curvature, planarly arranged Fresnel mirrors have been tested recently which require a considerably smaller curvature resulting in lower manufacturing costs as well as allowing for coverage of a larger area and less windage. With 450°C, a comparatively high working temperature was reached in such facilities[51].

As opposed to single-axis concentrating troughs reaching a concentration of up to a factor of 100 dish-Sterling systems and solar towers offer two-axis concentration and tracking and allow for higher concentration factors, heating up the heat medium in a receiver to considerably higher temperatures. Dish-Sterling systems utilise a rotational symmetric parabolic mirror with a gimbal mount which focuses solar radiation onto an absorber whose medium drives an electric generator via a Sterling engine. Single systems currently reaching about some 10 kW can be combined into a MW plant. In order to facilitate a high efficiency of the Sterling engine over a longer period of time, even outside of peak irradiation times of the daily pattern, the mirrors are slightly oversized. In the long term, electricity production costs of 10-20 c/kWh are considered achievable when using dish-Sterling systems[52].

Solar towers utilising large mirror areas are particularly suited for generating higher power within the umpteen MW range and promise to reach temperatures of 800-1,000°C or more. These temperatures permit both high temperature chemical processes and electricity generation. For the latter, molten salts[53] or – as preferred in European projects – water steam circuits are chosen which operate at ~550-650°C[54]. Herewith, typical steam conditions as required for conventional power plant technology can be reached and efficiencies of above 30% averaged over a year should be achievable. Developments are heading towards increasing efficiency via using hot air and steam in gas turbines with downstream steam turbines. In order to achieve these high efficiencies, cooling towers utilising evaporative cooling are required which necessitates fresh water supply in these very arid regions and causes additional investment and operating costs.

Currently, concentrated solar heat plants are being built having an integral power of 500 – 1,000 MW worldwide, 200 MW of which are in Spain alone[55]. An installed power of > 20 GW is expected by this industrial sector within a decade, based as usual on exponential growth and the expectation for corresponding political support. The cost-

---

[48] The largest facilities are AndaSol-1 (equipped with a molten salt storage unit for 7.5 hours) and Andasol-2 with 560,000 m^2 reflecting surface each and 50 MW_{el}. Worldwide, the construction of parabolic trough power plants with a total of >2 GW is in the pipeline.

[49] The upper limit of known heat transfer oils is 550°.

[50] DISS (Direct Solar Steam) Project, Plataforma Solar, Almeria.

[51] A 1 MW_{therm} testing facility on the Plataforma Solar de Almeria (DLR).

[52] Source: B. Hoffschmidt, Solar-Institut Jülich (Solar Institute Jülich)

[53] E.g. projects in the US. These molten salts can be used simultaneously as a storage medium.

[54] Several commercially operated solar tower plants are in operation in Spain and the US or under construction.

[55] Source: B. Hoffschmidt, S. Alexopoulos, Conference of the DPG (German Physical Society), Hamburg, 2009.

effectiveness of this type of electricity generation[56] can only be assessed conclusively once sufficiently large pilot projects have been evaluated in the long term, something which could be done within the scope of the DESERTEC or ESTELA initiatives[57]. Estimates based on experiences with Spanish power plants assume that the energy-related amortisation period is about 4-6 months.

The currently expected investment costs could result in electricity production costs of about 16 c/kWh[58] to which costs for transmission need to be added. It also needs to be asked whether an increase in productivity of solar thermal electricity generation (CSP) is possible which would make it competitive in the long run beyond regional electricity supply; in this regard, achieving operating times of 24 hours with high annual availability (co-firing of biomass if needed) is one of the most important issues. Electricity production costs at the level of fossil-based part load and perhaps base load generation are claimed for favourable sites (i.e. North Africa in terms of European interests)[59], which, however, cannot be inferred from a learning curve with largely stagnating technology. The negative aspects of an enormous market subsidisation have been mentioned in the context of photovoltaics and they need to be considered when embarking into solar thermal electricity generation.

Even though they are not the focus of this study, the political risks that exist with regard to services essential to societies such as electricity supply need to be pointed out when making corresponding long-term investments in third countries. In terms of solar or other power plants outside the EU a situation of political dependence and (un)reliability of electricity supply needs to be presumed which is basically comparable to that of fossil fuels. Co-operative economic development of the southern Mediterranean countries, however, is a central issue of EU foreign policies for various reasons. Proper electricity supply of the region itself is an essential prerequisite which could best be met in a climate-neutral fashion by solar thermal power plants. In the long term, the development of a web of economic connections is hoped for which should also advance reliability in terms of electricity supply. If solar electricity provision from northern Africa is extended to a level making up a not insignificant share of the European or German electricity supply, it may be noted that surplus electricity in the order of GW generated in that region can only be transmitted to other regions which are connected via HVDC lines; these are going to run to Europe, Europe being the main investor, particularly as other big customers are not going to be within reach even in the long term. If electricity transmissions are interrupted this also hits the producer with serious economic consequences since the non-transmitted amounts of electricity from solar plants are irretrievably lost as merchandise including the profits made from it – as opposed to the case of stored or long-term storable fossil fuels. Therefore, the supplying states will be highly interested in converting the available solar energy into electricity and supplying it.

---

[56] The IEA (IEA/PRESS (10)04, Valencia, 11 May 2010) expects CSP to become competitive at the most favourable sites around 2020 for part load and about 2025-2030 for base load generation via thermal storage units operating for 24 hours and names North America, North Africa and India with regard to the build-up of the largest electricity generation capacities and estimates that about half of the northern African electricity generation will be exported to Europe.

[57] See www.desertec.org, or Mediterranean solar plan (www.estelasolar.eu)

[58] Calculations by the author based on figures by Greenpeace "*energy [r]evolution 2009*" for investment volumes and day-to-day operating and maintenance costs per kW for 30 years of operating time and financing at 4.5%. Further, it was assumed that investment costs of 4,900€ / kW_{peak} will be necessary in the future (currently about 6,340$ / kW_{peak} - both figures provided by Greenpeace) for a plant with a storage unit extending the daily operating time by 5.5 hours into the evening which is equivalent to 3,000 kWh/a generated electricity, with 85% annual availability and with grid losses of 20% for a volume of 80% of the generated electricity.

[59] See, for example, Greenpeace, "*energy [r]evolution 2009*". Taking a cost degression from 7,530 $/kW to 4,320 $/kW by 2050 Assumed by Greenpeace as a basis, a non-subsidised cost-efficient operation at 5 c/kWh could be expected if 24 h electricity generation per day were possible by extending storage capabilities (current prices, excluding grid and electricity transmission costs).

II.6 Wind power

6.1 Wind power in Germany and worldwide

Thanks to a generous state-subsidised market introduction scheme, wind power has been developing rapidly in Germany since the beginning of the 1990s and has been the fastest growing renewable energy since then. At the end of 2009, slightly above 21,000 wind turbines with a total nominal power of 25.8 GW were in operation, generating 37.8 TWh of electricity in 2009 (7% less than in 2006 as 2009 was a poor wind year) equating to 6.3% of the total electricity production [1].

The amount of electricity generated by wind energy plants (WEPs) in 2004 exceeded, at 25 TWh, the amount generated by hydro power for the first time. In 2008, electric energy from WEPs had already increased to 40.6 TWh and contributed 6.4% of the total electricity generated (see Tab. 1). Worldwide, however, the contribution of wind power to electricity generation was only 1.2% in 2008 and was thus significantly lower than that of hydro power at nearly 16% [2] (in a study on the worldwide expansion of methods of CO_2-free electricity generation, the IEA estimates the share of wind power to increase to 12% by 2050 [3]).

	Installed wind power (GW)	Generated electric energy (TWh/a)	Average wind power (GW)	Annual full load hours	Share of total electricity generation
Worldwide	121.2	260	29.7	2145	1.24 %
Germany	23.9	40.6	4.6	1700	6.35 %

Tab. 1: Installed wind power, generated electric energy, average wind power, annual full load hours and share of wind power of the total electricity generation in Germany and worldwide in 2008 (sources: German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) [1], World Wind Energy Association [WWEA])

Germany, having been the trailblazer with regard to the construction of WEPs, has been outperformed by other countries: In 2008, new constructions in Germany, at a nominal power of 6.6 GW, were far behind the US (31.6 GW) and China (23.8 GW) and about on a par with India (6.6 GW) and Spain (6.1 GW).

6.2 Extension of wind energy, mainly offshore

Until recently, WEPs were built on land (onshore), preferably near the coast, where the wind blows much stronger than inland (see Fig. 1a). The average number of full load hours in Germany accordingly is between 1,000 in Bavaria and 2,200 in Schleswig-Holstein (of the total number of 8,760 hours a year). However, most onshore sites with good wind availability are already occupied and an increase of the total power can only be achieved by re-powering, i.e. replacing old WEPs with new, more efficient ones at the same location. There are increasing acceptance issues in this regard as the public reacts rather sensitively to new installations of larger WEPs with MW power (visual appearance, noise pollution, amongst other things).

In the future, a large number of new WEPs are going to be installed offshore, mainly because the wind blows much stronger and more evenly there than on land (see Fig. 1b) which results in a doubling of the number of full load hours (about 3,800 as compared to 1,800 onshore). Germany is taking a decisive step towards more efficient WEP sites by installing WEPs in its Exclusive Economic Zone (EEZ) in the North and Baltic Seas. The technical realisation is hampered, however, by the fact that the public wants the WEPs to be mostly invisible from land which has pushed the WEPs out to the open sea at water depths of 30 m or more.

Natural onshore wind conditions (open plain at 50 m height) Natural offshore wind conditions (open sea at 50 m height)

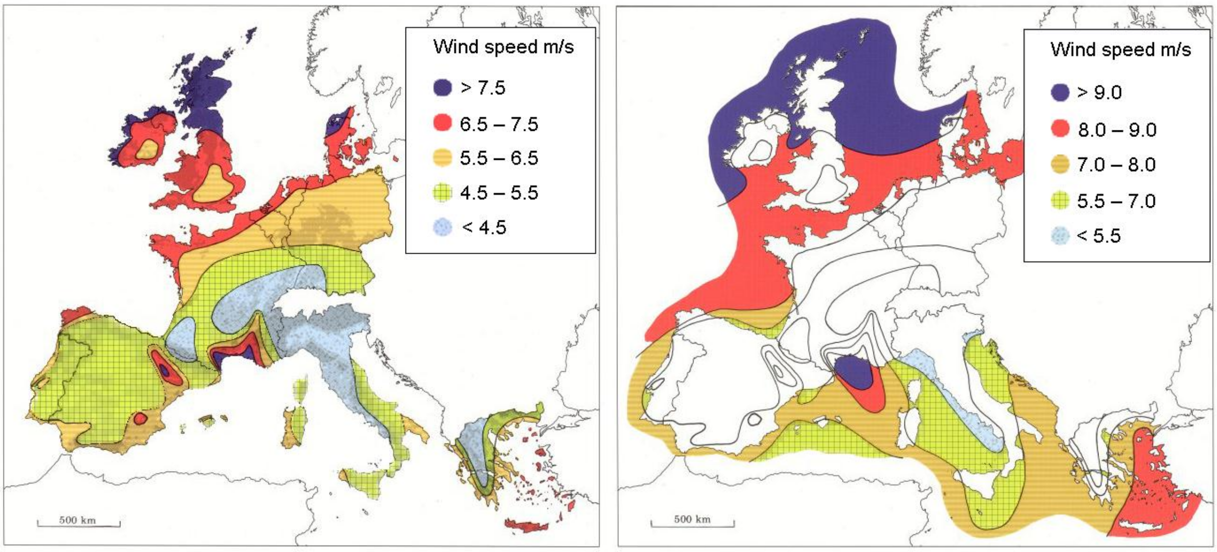


Fig.1: Wind conditions in Europe onshore (left) and offshore (right), local variations have been smoothed out. (Source: *European Wind Atlas*, © Risø National Laboratory, Roskilde, Denmark, simplified)

- The first German offshore wind farm, “Alpha ventus” (a joint venture between EWE, E.ON and Vattenfall), went into operation in 2009. It is located about 45 km north of Borkum at a water depth of slightly more than 30 m and has a total nominal power of 60 MW (12 wind power stations with 5 MW nominal power each). Investment costs were about 250 million euro in total, equating to costs of about 4,200 euro per kW installed power, excluding the costs for connecting to the German transmission grid.
- Plans for further extending wind power in the North and Baltic Seas have since been revised: an installed wind power of 2.7 GW is now expected by 2013 [4] (the grid study by the German Energy Agency (dena) [5] had forecast 9.8 GW by 2015). With regard to long-term expansion the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) antipates, in its reference scenario (“Leitszenario 2009”), an accumulated installed power of 9 GW by 2020 and 26 GW by 2030 [6].
- Building permits for nine offshore wind farms in the UK with a total capacity of about 25 (32) GW were issued [7]. Construction costs about 90 (110) billion euro.
- An accumulated installed offshore wind power of 7.1 GW is expected in Europa by 2013 [8]. Worldwide, a new study [9] expects an installed offshore wind power of 45 GW by 2020.

6.3 State-subsidisation in accordance with the German Renewable Energy Sources Act (EEG)

Even though WEPs in Germany in recent years have been raised to heights where the wind blows more strongly and is less turbulent (the rotor diameter and the hub height have doubled between 1996 and 2008) their average quality (number of full load hours per year) has not increased. The reason being that new WEPs are also being increasingly installed in less suitable (i.e. deprived of wind) locations, a process which is helped by the German Renewable Energy Sources Act (EEG): first, the prerequisites for the worthiness of subsidisation are very low (60% of a reference yield), and second, the formula for the extension of the (higher) initial compensation beyond the first 5 years gives support to unsuitable locations[1].

[1] This becomes clear when examining the following three examples: 1) yield = 65% of the reference yield: the higher initial compensation remains for the whole time period; 2) yield = reference yield: the lower basic compensation begins after 5 + 6 years; yield = 150% of the reference yield: the basic compensation already begins after the end of the first 5 years.

Currently subsidisation of wind power as per the EEG is about 3 billion euro per year (fed-in amount of electricity was 38 TWh in 2009, average feed-in compensation about 8 cent/kWh) which is passed on to the electricity customers.

6.4 Wind energy demand for conventional controlling power and reserve capacity

The biggest disadvantage of wind energy is its great temporal fluctuation, i.e. both its daily and seasonal fluctuation. The difficulty of matching the energy supply, which can never be predicted exactly, with the respective electricity demand increases with the increase in the share of wind energy of the total electricity generation of course. Already today, with a share of wind energy of about 6%, the limit of what is technically possible is being exceeded at times as demonstrated by the fact that extremely windy hours can result in surplus electricity generation which in turn results in negative electricity prices on the German electricity stock exchange.

In order to get a feeling of the considerable demands for controlling power and reserve capacity related to the extension of wind energy, it is useful to examine the results of a new study by the "Institut für Energiewirtschaft und Rationelle Energieanwendung (IER; Institute for Energy Economics and Rational Application of Energy)", University of Stuttgart [10], in which the wind power credits of the installed WEPs were calculated using certain simplified assumptions[2] (see Fig. 2).

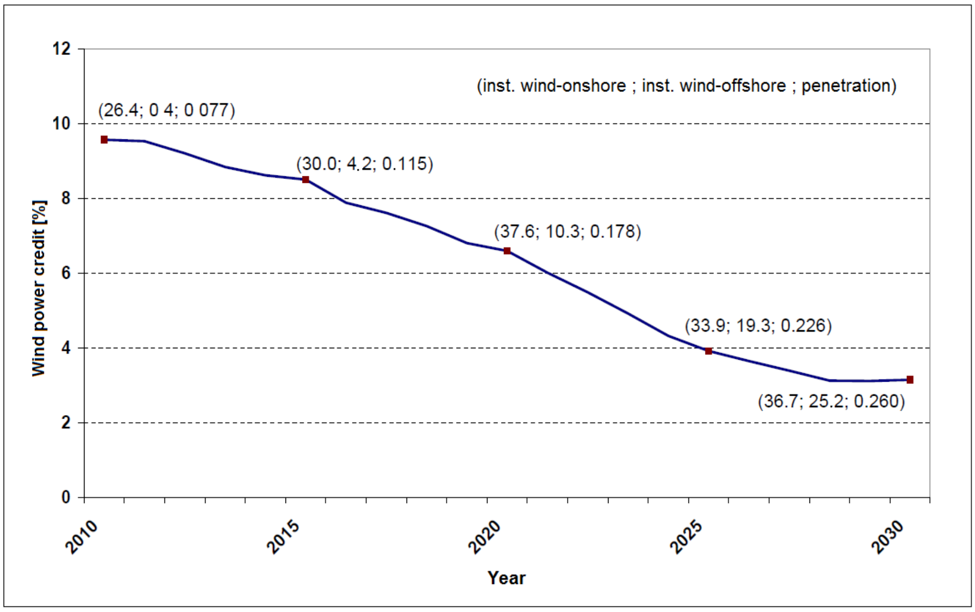


Fig. 2: Wind power credit according to the installed wind power (onshore plus offshore) and its "penetration" (assigning these figures to certain dates is an estimation) [10]).

The term power credit refers to the amount of installed conventional power that can be replaced with wind power without altering the level of reliability of the mixed system as opposed to the level of reliability of the conventional initial system. It understandably decreases with increasing "penetration", that is, with the share of electricity generation from wind energy of the total electricity generation. The calculations by the IER took the WEP capacities actually installed in 2008 as their basis and anticipated a mix of new installations of onshore and offshore power by 2030.

[2] No change in storage capacity and no interconnection between geographically more distant WEPs in Europe during the period under consideration, i.e. the next 20 years, amongst other things.

As depicted by Fig. 2, the calculations for 2010 show a power credit of 10% for the installed WEP which decreases with an increasing extension of wind power to about 3% by 2030 (assuming a supply reliability of 99%). As a consequence, the initial 90% and later on 97% of the installed wind power needs to be backed up continuously by conventional power plants. In general, building wind energy plants does not, therefore, make conventional power plants obsolete (and the investment costs they incur unnecessary) but only saves a part of the fuel costs they incur[3].

Let us now consider the controlling power (minute and hour reserves) which needs to be provided in order to compensate for uncertainties in the wind prognosis, taking into account both the form of positive as well as negative controlling power (its amount depends on the quality of the prognosis, of course). In the grid study by the German Energy Agency (dena) [5], an installation status of 36 GW was examined (forecast for 2015, now presumably achieved by 2020), which required a maximum positive controlling power of 7.0 GW (19% of the installed wind power) and a negative one of 5.5 GW (15%).

This minute and hour reserve must be provided, as shown in the grid study by the German Energy Agency (dena), by fast controllable conventional power plants (so-called peak load power plants, especially gas turbines) and, perhaps, by adjusting the operating control of existing pump storage power plants[4] (storage needs to be full). Nuclear power plants are also able to provide controlling power in the required time frame (see subchapter II.2.2-b).

In the long term (time horizon 2030 or beyond), there is the general idea that several million electric vehicles in Germany will be an integral part of the grid and thus will be able to significantly contribute to storing and controlling the fluctuating regenerative energy sources wind and sun. Alternatively and in the long term maybe more realistically, the demand for controlling power can be significantly reduced by integrating wind farms at different sites in Europe and northern Africa into a European grid (see e.g. [11]). In the meantime, it would be advisable to also include the feed-in of wind power into the grid into the supply- demand balance and make, for instance, the feed-in imperative with regard to wind power more flexible.

6.5 Required grid extension

In order to be able to transport the large amounts of electricity from the wind farms in the North and Baltic Seas to the consumers in Western and Southern Germany, the grid which evolved over many decades (consisting of many decentralised electricity providers and relatively short lines to consumers) needs to be considerably extended and newly structured (see chapter III.1). The grid study by the German Energy Agency (dena) [5] expects the integration of 36 GW wind power into the German transmission grid to require new installations of 380 kV lines amounting to about 850 km (on 8 new cable routes) by 2015, new lines amounting to about 1,900 km (preliminary result) by 2020, and additionally a considerable reinforcement of existing cable routes and new components for load flow control and reactive power generation.

First, the electricity needs to be transmitted from the offshore wind farms to the coast via submarine power cables. In this regard, high voltage direct current transmission (HVDC) technology has proven to be advantageous. In this context, the sensational billion euro project (estimated costs of about 30 billion euro) must be mentioned [12] which is intended to connect German, British and Danish offshore wind farms with hydro power plants in Norway via high voltage submarine power cables on the floor of the North Sea as well

[3] As a consequence, CO_2 avoidance costs of wind energy will be at 40-80 €/t CO_2 by 2015 according to estimates by the German Energy Agency (dena) [5] and thus are relatively high in comparison to other options of CO_2 avoidance.

[4] The potential for suitable pump storage power plants is geographically limited in Germany and almost depleted. Compressed air energy storage is an interesting alternative, but it is still in a state of development and considerably more expensive (see chapter III.2).

as wind and solar power facilities on the European continent. This way, an international electricity grid extending across many borders would be created in Europe for the first time.

6.6 Summary and outlook

Wind power makes the largest contribution by far to the electricity supply via renewable energy sources: In 2009, at 38 TWh, wind energy plants already provided 6.3% of the generated electricity. With regard to long-term extension, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) expects a contribution of wind energy at 96 or 163 TWh/a (about half of the latter generated offshore) by 2020 and 2030 respectively in its updated reference scenario ("Leitszenario 2009") [6], equating to a share of 15.5% or 26% of electricity generation (assumed to be constant at 620 TWh).

Other European countries also have ambitious plans for the extension of wind energy, particularly the UK which is mainly investing in offshore wind farms near the British coast. In order to be able to generate economically competitive electricity from wind energy, wind energy plants need to be installed where wind conditions are optimal, i.e. in Europe along the northern coast of Spain, France and Germany as well as in Denmark and the UK and in the open sea (see Fig. 1).

As the amount of wind energy (just as photovoiltaics) fed into the grid fluctuates strongly, its prognosis will always remain uncertain to a certain extent, and it is therefore advantageous to connect as many wind energy facilities at as many different sites as possible to other, different types of renewable energy sources. The creation of a European integrated electricity (super) network, therefore, is one of the most important prerequisites not only for the success of wind energy but for all efforts in general to meet the long-term electricity demand via renewable energy sources.

Notes and references

[1] Bundesministerium für Umwelt (BMU; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), *Entwicklung der erneuerbaren Energien in Deutschland im Jahr 2009* (German only; translation: *Development of Renewable Energies in Germany in 2009*), as of 18 March 2010, Tables 5 and 6

[2] International Energy Agency (IEA), World Energy Outlook 2009, Paris 2009, p.101

[3] International Energy Agency (IEA), Technology Roadmap, *Wind energy*, Paris 2009

[4] FAZnet (online edition of German newspaper FAZ, Frankfurter Allgemeine Zeitung), 7 January 2010 (source: BTM Consult)

[5] Deutsche Energie-Agentur (dena; German Energy Agency), *Energiewirtschaftliche Planung für die Netzintegration von Windenergie in Deutschland bis zum Jahr 2020*, (German only; translation: *Energy Economical Planning for the Grid Integration of Wind Energy in Germany by 2020*), Cologne, 2005

[6] Bundesministerium für Umwelt (BMU; German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), *Leitszenario 2009 (Kurzfassung)*, (German only; translation: *Reference Scenario 2009 [Short Version]*), August 2009, paragraph 8 and Table 2

[7] Welt.online and heise online, 8 January 2010

[8] RWE innogy factbook (2009)

[9] Emerging Energy Research, Press Release, 18 December 2009

[10] Institut für Energiewirtschaft und Rationelle Energieanwendung (IER; Institute for Energy Economics and the Rational Application of Energy), University of Stuttgart, 2009

[11] G. Czisch and J. Schmid, *Low cost but totally renewable electricity supply for a hugh supply area – A european/trans-european example*, in *Klimaschutz und Energieversorgung* (ed. Martin Keilhacker), German Physical Society – Working Group on Energy, p.133-160, 2006

[12] FAZ (German newspapaer FAZ, Frankfurter Allgemeine Zeitung), 4 January 2010

II.7 Hydro power

Hydro power is the oldest method of electricity generation from renewable energy sources. Today, about 16% of the worldwide electricity demand is met via hydro power. Electricity from hydro power is almost entirely generated from running water plants and reservoirs. Apart from these methods, there are further ways of utilising hydro energy:

- waver energy
- ocean currents
- tidal energy
- osmosis
- helio hydroelectricity
- ocean thermal energy

7.1 Run-of-river power plants, reservoirs

Electricity generation from hydro-electric power plants at river barrages for large-scale utilisation began in Germany in the final decade of the 19th century. About 7,500 run-of-river power plants with a power of 4,700 MW (electricity generation 2006: 21.6 TWh) exist in Germany today. Hydro power contributes a share of about 38% of the electricity generation from renewable energies and of about 3.5% of the total electricity demand[1] in Germany.

Modern run-of-river power plants typically reach a total efficiency of about 94%; therefore, an increase in efficiency does not result in a considerable increase in power output.

Run-of-river power plants are used extensively. For instance, the drop in elevation of the river Moselle is ultilised via a series of 14 barrages between Koenigsmacker (France) (149 m height above sea level) and Münden (40 m height above sea level). Taking the interests of inland waterway transportation into account, a significant increase in the capacity of the run-of-river power plants cannot be expected with regard to the German inland.

Smaller, non-navigable rivers in the Alps and the German low mountain ranges are often equipped with river dams to form reservoirs – there are more than 300 river dams in Germany, 86 of which have a volume >10 and 12 >100 million cubic meters (the largest reservoirs in the world are again ten times larger). They also serve other important purposes (drinking or service water supply, flood control, raising low water levels or water level regulation etc.). River dams used for electricity generation also usually serve some of these purposes. As opposed to hydro-electric power plants located on diverted parts of larger, navigable rivers whose barrages can usually not be utilised, or only to a small extent, for regulating the water level, reservoirs located on smaller rivers without waterway transportation have the advantage of allowing for significant water level changes. Storage according to the seasons can be achieved this way and the power output can be adjusted to the demand. However, the available volume is not sufficient for a relevant level of long-term storage for the purpose of electricity generation.

If two reservoirs can be constructed at different heights, a pumped storage power plant can be built which is capable of storing electricity supplied by other sources. At low load times, water is pumped to the upper reservoir using electricity generated from other sources and subsequently is available for electricity generation at heavy load times.

[1] Source: ENBW (Energie Baden-Württemberg AG; energy company)

The largest pumped storage power plant in Germany is Goldisthal (startup 2003/4) with a volumetric capacity of about 19,000 and 12,000 million cubic meters for the lower and upper reservoirs respectively, the latter being located 350 m above the former. Its capability to generate electricity is about 8.5 GWh at a maximum power of 1.06 GW. The German grid is equipped with 33 pumped storage power plants providing together a maximum power of 7 GW (90 GW worldwide); their storage capacity is about 50 GWh equating to about 6 hours in full load operation. The big advantage of these types of power plants as opposed to thermal power plants is their short powering-up times – full load can be achieved within a few minutes. For this reason they are used, amongst other things, for supplying balancing energy (about 7.5 TWh per year) even though the pumping up of water consumes about 15-30% of the electric energy employed[2]. Run-of-river power plants also contribute to providing balancing energy.

Run-of-river hydro power and reservoirs do not emit CO_2 during operation and offer, like pumped storage power plants, a cost-effective and fail-safe operation with relatively low maintenance requirements and quick adjustment of the generated power to demand. Generally speaking, hydro power has a very low safety risk. Disadvantages are severe alterations of the landscape and adverse effects on the environment and low acceptance of new projects as well as possible negative effects on inland waterway transportation plus high investment costs.

7.2 Marine energy

7.2–a Wave energy

Wave energy utilises the potential energy of the wave which depends on the difference of the body of water in the wave crest and the wave trough. Wind is the driving force which is why the conditions with regard to wind and wave energy are generally comparable at sea. At deep water conditions, the typical average wave heights of 1.5 m and wave lengths of about 50 m in the German Bight provide an average power of about 10 kW per meter of lateral extension which corresponds to an area requirement of 1 m^2 per installed kW of a power plant[3]. In order to generate 1 GW under these conditions, a wave energy power plant would need to be about 100 km in length which may be folded but the fact needs to be considered that a distance of several tens of kilometers in the wind direction is required to excite the waves. That is, in wave farms (similar to wind farms) with closely packed rows the upwind energy converters shadow other energy converters if they extract a noticeable share of the wave energy. As the power increases with the second power of the wave height (in shallow water the exponent is about 2.5)[4], a significantly larger amount of energy is available in winter with its stormy weather than in summer, and locations with generally stronger waves (mainly at higher geographical latitudes) are advantageous. At a wave height of 5 m the wave power is already about 140 kW per meter of lateral wave extension; at 21 m it would be 3.8 MW – however, the distinctly broad spectrum of wave heights and lengths during storms in deep water needs to be considered. In German waters, rather low values are found. For this reason, wave energy is currently only of minor interest to large-scale electricity generation in Germany, but other regions in Europe, e.g. Scotland, the Atlantic coast of Portugal or the Bay of Biscay are well-suited for this purpose.

Systems utilising surging billows can also be expected to generate about 10 kW per meter of coastline for an average wave amplitude of 2 m and an efficiency of 30%. Such facilities can be combined with facilities for coastal and harbour protection in order to reduce investment costs. As only the coastline can be used, they have a significantly lower potential for electricity generation and compete with other forms of utilisation.

---

[2] Source: ESA, http://www.electricitystorage.org/site/technologies/pumped_hydro/

[3] Source: U. Leipzig. This is a rough estimate of the net area of the energy converter.

[4] Graw, K.-U. *Wellenenergie* (German only; translation: *Wave Energy*) http://www.uni-leipzig.de/~grw/lit/texte_099/40__1995/m8.pdf

Different systems for the utilisation of wave energy have been proposed and some of them are being tested. Some have been in operation for some time, particularly oscillating water column systems in which wave energy compresses air in a reservoir which drives a (Wells) turbine. Such systems have been employed for electricity generation in surface marker buoys for the last two decades. In general, farms comprised of many small devices seem to be preferable to a single large system. Important issues are storm resistance (a substantial number of experimental plants have been destroyed by winter storms) as well as corrosion stability. In principle, wave energy has a great potential and could also be used to some extent in German waters. However, much research and development is required particularly as field tests have shown that the extreme peak loads, at a factor of 100 above the average wave power, generated during hurricanes, have not been mastered yet.

7.2–b Ocean current

The utilisation of steady and strong ocean currents for electricity generation has been discussed for a long time, in Europe for instance with regard to the English Channel, the Straits of Gibraltar or the Straits of Messina. No power plant has been built yet. Ocean current speeds above 2 m/s are considered the minimum requirement for the possible utilisation by an ocean current power plant. The issues here, apart from the question of the actually available potential (which is probably rather small compared to wave energy), are environmental compatibility, compatibility with competing use (e.g. fishing) and long-term sea water durability of the facilities. German waters appear to be less suited for large-scale utilisation.

7.2.–c Tidal energy

The average oceanic tidal range is about 0.5 m. Near the coastlines in many parts of the world it is significantly amplified by resonance effects and can reach up to 15 m in some bays. The relative positions of the sun and moon and the wind conditions also have an effect (spring tide). Tidal power plants can be installed as opening and closing dams or they can utilise the currents of the rising and falling sea. The power is almost proportional to the enclosed area and the square of the tidal range. Worldwide, there are several dozens of bays which are attractive with regard to tidal energy generation, such as the Bay of Rance near St. Malo where an annual average of about 70 MW of electric power with an availability of >93% has been generated since 1966 by a water basin of 22 km^2 and tidal ranges between 12 and 18 m [5]. German coastlines are not suited for the utilisation of this energy source. The technological problems have been underestimated with regard to existing power plants using enclosed pools for storing the high tide water until the onset of the low tide, as well as the issues of corrosion and incrustation and ecological damage. Possible future plants, therefore, probably need to be driven by underwater turbines, i.e. they would correspond to the concepts discussed for ocean currents.

7.2–d Osmosis

This type of power plant utilises the salinity gradient between sea water (3.5% salt) and fresh or brackwater and thus the inversion of the principle of sea water desalination. Two filtered currents of sea and fresh water respectively are connected via a semipermeable membrane. An osmotic pressure results which is proportional to the differences of the salt concentration at the membrane. It is 26 bar for sea water with a salt

[5] Data for the time period 1982-1994. The power plant does not only utilise the ocean currents of the falling and rising tides twice each day but also utilises pumps in addition in order to be able to supply economically valuable peak electricity timed to demand. (Source: EDF; nuclear energy company)

content of 3.5% and, as a consequence, fresh water diffuses through the membrane into sea water and in so doing increases its volume and pressure. At optimum conditions, about half of the pressure, i.e. about 14 bar, can be utilised to drive a turbine[6]. The first of such power plants with a power of 2-4 kW and a membrane of about 1,000 m^2, went into operation in Norway, near Oslo, at the end of 2009.

The central issue of the power plant is its membrane which needs to be very thin in order to have a diffusion resistance that is as low as possible and needs to offer long-term stability at the same time – time periods of about 7-10 years are envisaged. A composite membrane developed in Germany with a thickness of 0.1 µm is used in Norway[7], resulting in a power of 3 W/m^2. The long-term goal is at least 5 W/m^2. In other words, a power plant with a power of 10 MW would need a membrane of 2 million m^2 in size and an influx of 10 m^3/s of fresh water. The initial investment costs are estimated to be much higher than those for other renewable energy sources.

The theoretical potential of such power plants is estimated to amount to up to about 1.4 GW in Norway for its total coastline with many small rivers; figures not much higher than this apply to the total amount of water carried to the North Sea by the river Rhine. This exemplifies that the potential of this type of electricity generation is strictly limited in practice.

7.2–e Helio hydroelectricity

Water could be transported over 80 km from the coast via a canal to depressed areas, such as the Dead Sea at 400 m below sea level and the height of fall would be utilised by turbines; the water may subsequently evaporate in the depressed area. The electric power generated could amount to up to about 20 GW_{el}[8]. In Central Europe, there is no possibility for generating energy in this way.

7.2–f Electricity generation from ocean thermal energy

The temperature gradient between water layers close to the surface and deeper layers can be utilised for electricity generation. The concept was already conceived at the end of the 19th century and realised for the first time in 1930[9]. In Keahole Point (Hawaii), an Ocean Thermal Energy Conversion (OTEC) facility with 52 kW_e and a net generation of 15 kW_e was in operation from 1979 onwards. Since then, experimental plants have used either open or closed cycles (i.e. using heat exchangers)[10]. The largest facilities with a net electric power of 50 kWe or 40 kWe were operated in Hawaii and Japan respectively. Currently, the installation of a 5-10 MWe pilot facility is being discussed. Only after results with regard to facilities of this size are available can the practical potential of this technology of electricity generation be estimated. Assessments of the theoretical potential are underway and the technology is being explored by several countries[11,12].

---

6 Final report *Salinity Power* (2004); http://cordis.europa.eu/ documents/documentlibrary/82766661EN6.pdf

7 K.-V. Peinemann et al., *Membranes for Power Generation by Pressure Retarded Osmosis*, in: K.-V. Peinemann, S. Pereira Nunes (Hrsg.), *Membranes for Energy Conversion*, (Wiley-VCH, Weinheim 2007).

8 B. Diekmann, K. Heinloth, *Energie* (German only; translation: *Energy*), Teubner (1997)

9 Jacques Arsène d' Arsonval, 1881. The first 22 kW facility was constructed by G. Claude in Cuba in 1930.

10 http://www.nrel.gov/otec/achievements.html

11 http://www.lockheedmartin.com/data/assets/ms2/pdf/LM_OTEC_Brochure_FINAL.pdf,

12 GreentechMedia, OSO OSEGUERA APRIL 13, 2010

7.3 Outlook

In Germany and Central Europe inland-generated hydro power contributes in an excellent way to a climate-friendly electricity supply. Its potential, however, has been mostly exhausted considering environmental issues and competing use.

Marine energy, however, is essentially not yet being utilised. Systems covering a large area offer the largest potential in this regard. Systems utilising only the coastlines can be useful when combined with facilities for coastal and harbour protection and offer favourable investment costs; their potential for electricity generation is only locally important and not relevant to the overall electricity demand. In general, considerable research and development close to the market is needed for making use of marine energy. Utilisation of ocean currents, osmosis, helio-hydro regions are to allow for constant electricity generation. Wave energy results from the amount of wind actually available, but, in suitable regions open to large areas of the ocean, will fluctuate less than wind due to swells. If storm resistance and long-term operation can be demonstrated, it should be possible to utilise wave energy at costs comparable to those of wind energy on a large scale: estimates assume about 10 c/kWh[13,14] in the long term – some prototypes are already in operation at these costs. The climate and environmental balance of marine energy should be favourable. The potential in German waters is comparatively lower than that of other countries (Norway, the UK, France, Portugal in Europe). The utilisation of marine energy could become a huge market in the medium term.

[13] Graw, K.-U. *Energienutzung der Meereswellen* (German only; translation: *Utilising the Energy of Ocean Waves*), Physik in unserer Zeit (German only; translation: Physics in Our Time), February 2002

[14] Thorpe, T. W. *A brief Review of Wave Energy* Report produced for the UK Department of Trade and Industry (1999), ETSU-R120

II.8 Electricity from geothermal sources

8.1 Introduction

The earth is a heat reservoir of 10 – 20.10^{30} Joule (J) of which about 10^{26} J are contained in the outer earth's crust at depths of up to 10 km. In the balance, this heat content results from heat loss at the earth's surface, the residual heat from the formation of the earth and a continuous heating via the decay of long-living radioactive isotopes (U-238, U-235; Th-232 and K-40) which can be found accumulated in the earth's continental crust in particular. In granitic rock, heat generation is about 2.5 μW/m^3; in basaltic rock it is about one order of magnitude lower. The average heat transport from the deeper earth's crust is about 60–65 mW/m^2, equating to 10^{21} J/a globally.

Up to depths of 1.5 m, there are daily fluctuations of the temperature at the earth's surface and up to depths of 30 m there are seasonal fluctuations. Towards the earth's inner core, temperatures increase with an average of 25-30 °C/km; thus, the required temperature level of 150 °C for electricity generation is usually found at depths of >5,000 m only. In volcanic areas where magma rises into the upper earth's crust (10-15 km depth) consisting of sediments, metamorphic rock and granites, the temperature increase can be significantly higher. Areas providing such a high enthalpy already at such low depths, are found in Europe, e.g. in Iceland, Tuscany or the Pannonian Basin as well as in the adjacent area, particularly in western Turkey.

The presence of a liquid (water, sole) at a high permeability can considerably increase the heat transport via convection. For this reason, convective (hydrothermal) resources are mainly utilised for electricity generation at present. The geothermal resources for electricity generation available in Germany are mostly conductive (petrothermal) systems whose heat, stored in deep rock formations, needs to be exploited without utilising their natural hydraulic.

8.2 Technologies

Deep geothermal energy usually requires a closed liquid loop with at least one injection well and one production well exploiting a sufficiently hot aquifer. Facilities with a larger number of wells (geothermal fields) do not exist in Germany yet. The hot water loop is closed by a heat exchanger above ground and the cooled down water is returned to the field via the injection well. The extracted heat is passed on to a turbine in a secondary heat and liquid loop (due to the comparatively low inlet temperature conceived as an organic Rankine cycle) for electricity generation.

Hydrothermal systems require aquifers with a sufficient natural hydraulic permeability; in practice, hot water generation of at least 100 m^3/h is required. While a certain temperature can always be reached via a corresponding drilling depth, this precondition limits the number of possible locations considerably.

Well-flow conditions with regard to *petrothermal systems* can be improved by methods of engineering technology, so-called engineered geothermal systems (EGS) technologies. This can result in the creation of an artificial underground heat exchanger from which geothermal heat is extracted via surface water. Hydraulic fracturing or acidising are two examples of methods by which means sufficient hydraulic permeability can be created in rock formations with low permeability and the cost-effectiveness of geothermal energy generation can be improved. Existing cracks in crystalline (and also sedimentary) underground reservoirs are widened or new ones are created by injecting water at high pressure (stimulation) in order to connect a sufficiently large volume (>0.2 km^3) to the well and create a large surface for heat exchange (typically several km^2). The heat exchanger loop exists mostly between two or more (injection and production) wells at (underground) distances of several 100 m with the lower wellheads open for the liquid loop over several 100 m.

All technological system components necessary for the exploration and utilisation of geothermal energy sources are available today.

8.3 Application and potential

Electricity from geothermal energy has the advantage of continuous daily and seasonal availability over electricity from wind or photovoltaics and also allows for a cost-effective utilisation of the residual heat. Geothermal power plants generated an average annual electric power of about 10.5 GW in 2009[1], 3.7 GW of which was in the US and Mexico, 3 GW in the Phillipines and Indonesia, 800 MW in Italy (Larderello) and 450 MW in Iceland where geothermal energy contributes 19% of the electricity supply by now. Worldwide thermal energy generation increased by 16% in the 4 years 2005-2009 and it is assumed that the possible utilisation could be several hundred GW_e – mainly in Africa, Central and South America, Asia and the Pacific countries – and 50 GW_e in Europe at the end of the century[2]. Almost all power plants are located in regions with geothermal anomalies which provide high enthalpy. Germany, however, basically only has resources for geothermal electricity generation which require wells of at least 3,000 but mostly >5,000 m depth in order to reach a minimum temperature of about 150 °C necessary for efficient electricity generation. In Germany, about 95% of the geothermal potential is explorable only via petrothermal systems technology.

In order to calculate the theoretical potential for geothermal electricity generation in Germany, a useable volume of rock formations which equates to a third of the area of Germany with a thickness of 2 km [3] is assumed, with a geothermal heat reservoir of about 2 Terajoule per km^3 and degree Celsius. If this reservoir is utilised, its temperature will decrease as the heat generation (~2.5 kW/km^3) and the basal heat flow from the earth’s mantle cannot compensate for the heat extraction. A cooling down of the rock formation by 1°C (possibly regarded as a maximum allowable temperature change) could result, assuming an overall efficiency of ~10%, in an overall electricity generation of 10-15 GW over a period of 100 years[4] – and more, if a larger temperature difference is considered acceptable or deeper horizons can be reached by drilling. Due to the extraction the temperature gradients increase which, combined with existing convection, lead to acceleration of the heat transport compared to the unhindered conductive one. However, a period of the same length of time as the useful life of the reservoir or even up to perhaps 1,000 years could pass before the original temperature has been more or less restored. In the meantime, wells need to be drilled in a so far untapped area or other depth ranges.

Geothermal electricity generation is only in its infancy in Germany. The use of aquifers without specific treatment of the reservoir is tested in a heat led combined cycle power plant in Neustadt-Glewe (Mecklenburg-Western Pomerania, Germany) with about 210 kW nominal and 137 kW average power, running reliably since 2003. Comparatively favourable conditions with up to 200°C at a depth of 5,000 m are found in Soultz-sous-Forêts, just beyond the German border in Alsace, as is generally the case in the northern part of the upper Rhine valley. There, the Hot-Dry-Rock (HDR) technology has been tested as part

---

[1] According to the International Geothermal Association IGA

[2] Bertani, *Long-term projections of geothermal-electric development in the world*. Proceedings, GeoTHERM Congress, Offenburg/Germany, 5–6 March 2009

[3] That is about 250,000 km^3. See Kaltschmitt et al. (ed.): Energie aus Erdwärme (German only; translation: *Geothermal Energy*), Stuttgart 1999

[4] When extracting 100 MW (equating to 10 MW_e at 10% efficiency) from 1 km^3 of rock formation, its temperature decreases about 8° in 10 years. As a result, however, the efficiency decreases significantly as well.

of a European project since 1987. This facility mainly used for research, in particular into the field of reservoir stimulation, generates 1.5 MW_e. Other projects in the northern part of the upper Rhine valley (Landau) and in Unterhaching, Bavaria, utilise hydrothermal resources at a depth of about 3,000 m for electricity and heat generation with an[2] added power of 6 MW_e (as of 2009). The underground area utilisation by geothermal power plants is about 1 km^2/10 MW_e, the aboveground net area[5] required is, depending on the situation, about 1,400-2,300 m/MW_e.

Already today geothermal energy is able to play an important role at favourable locations featuring geothermal anomalies. This is demonstrated by, for example, the geothermal system in Larderello (Tuscany), utilised for electricity generation since 1904, which feeds 800 MW electric power into the Italian grid at competitive prices. However, here too, the original upper reservoir was depleted by overuse, and a lower reservoir is being utilised today in such a way that it is expected to remain in balance in the long term.

8.4 Costs and environmental issues

Investment costs of geothermal electricity generation via EGS are determined by exploration, drilling, reservoir treatment, the thermal liquid loop as well as the aboveground power plant and are currently estimated to be about 15€/$W_{nominalpower}$, with drilling costs dominating at >70%. The amortisation of the necessary capital, depreciation, taxes and duties account for about 80% of the day-to-day operating costs and the actual operating costs account for only about 20%. Overall, on the basis of the currently available technology and normal geothermal temperature gradients, electricity generation costs of 26-32 c/kWh can be expected. Heat, on the other hand, can be generated at a price of about 6 c/kWh.[6] In view of avoided external costs, CO_2 avoidance has to be considered in particular: Life cycle analyses of electricity generation via EGS yield figures of about 60 g CO_2/kWh based on the current power plant mix; whereby the energy input of a geothermal power plant of >80% is determined by the construction. The energy pay back time for regular temperature gradients is currently 4-5 years[7].

Both the electricity generation costs and the energy pay back time are reduced significantly if reservoirs with higher temperature and/or lower drilling depths can be utilised (if a temperature of e.g. 160° instead of 150° is found, electricity generation costs are reduced by 30%[8]). Decreasing electricity generation costs can be expected under regular geothermal conditions as well. The main goal here is the (further) development of efficient and reliable stimulation approaches as the net energy extraction from a reservoir can be improved significantly at a comparatively low expenditure. Drilling costs are of particular importance due to their large share of the overall investment costs. Current exploration and drilling technology is dependent, to a large extent, on the developments in the fields of the oil and gas industries and an optimisation with regard to the specific conditions of geothermal projects is possible. Improved exploration technology should be able to reduce the number of aborted drillings and the necessary new drillings (required for maintaining the yield of the reservoir), as well as the (cost-intensive) duration of the drillings. After all, greater depths have been reached with state of the art drilling technology in recent years and this development is going to continue. This should allow for exploring reservoirs with higher enthalpy – having a correspondingly positive effect on electricity costs. Overall, electricity generation from geothermal energy sources is still in its early stages – particularly with regard to electricity generation under regular geothermal conditions. Therefore, an increase

---

5 In addition to areas covered by pipelines which are compatible with e.g. agricultural activities. See Tester, J.W. et al. (eds.), 2006. *The Future of Geothermal Energy Impact of Enhanced Geothermal Systems on the United States in the 21st Century.* Published by the Massachusetts Institute of Technology.

6 Frick, S. et al. to be published in E. Huenges (ed.) *Enhanced Geothermal Systems, Geothermal Technology for Resource Assessment, Exploration, Field Development and Utilization*, Wiley Ltd., being printed

7 Frick, S. et al. *Life cycle assessment of geothermal binary power plants in Energy* (2010)

8 Frick, S. et al. to be published in E. Huenges (ed.), loc. cit.

in productivity with considerable cost reduction is to be expected for the worldwide utilisation of this particular method of electricity (and heat) generation.

Geothermal facilities have caused a stir in connection with earthquakes, such as in Basel and Landau. Stimulation of the underground heat exchanger can cause or contribute to seismic activity – it must be noted in this regard that geothermally attractive fracture systems are usually found in areas of considerable tension in the bedrock, and thus the deep injection of water at high pressures for stimulating the reservoir can lead to relaxations of these tensions. Geology plays an essential role in this regard, for instance, gneiss rock mainly reacts in a ductile way to variations in pressure whereas granites exhibit a higher risk of notable seismic reactions. The exploration of seismic risks and the possibilities of minimising them thus is a central issue of ongoing geothermal research and development[9].

The geothermal liquid loop needs to be kept closed, also in order to avoid aboveground effects on the environment – particularly by CO_2 but also by sulfuric or other gases. This is not the case yet with regard to present high temperature geothermal power plants. Likewise, an organic Rankine cycle, if used, needs to be closed. When applying these measures, it can be expected that state of the art geothermal electricity generation is virtually emission free. In view of the planned sequestration of CO_2 from fossil-based power plants, the dual utilisation in areas with geothermal energy generation requires attention. The depleted (sedimentary) natural gas and oil fields and aquifers, which are currently discussed with regard to the injection of liquid CO_2, are usually located high above the geothermal reservoirs suitable for electricity generation, which means no direct adverse effect is to be expected. However, impacting such higher horizons with pressurised CO_2 would pose high demands on the leak-tightness of the geothermal borehole. Regulative measures must be taken in order to ensure that the deeply injected CO_2 cannot leak in unacceptable amounts.

8.5 Outlook

In Germany, the potential of geothermal energy for electricity generation is similar to that of photovoltaics but has considerably lower back-up requirements due to the absence of daily and seasonal variations and high plant availability and therefore is much more attractive. Worldwide, geothermal electricity generation has a very large potential, particularly via EGS technologies. Its further development in Germany, therefore, should not be supported in view of self-sufficiency only, but also and particularly with regard to the German industry gaining a large share of the rapidly growing international geothermal energy market.

[9] Apart from that, isolated deformations of the earth’s surface causing building damage resulted from geothermal drilling without sufficient exploration as water inrush was caused in anhydrite layers (Staufen im Breisgau).

II.9 Fusion power plants

9.1 Fundamental physics and state of development

Nuclear fusion is a carbon-free energy source. It utilises the non-radioactive feedstock fuels deuterium and lithium and it is expected that its utilisation can be made safe without any long-living radioactive waste remaining. These advantages are an incentive for the considerable efforts made in this area worldwide: The goal of research and development is to make fusion reactors based on the D-T reaction (D + T = He + n + 17.6 MeV) available for application by the mid-21st century; for these developments, above all the concept of magnetic confinement is being pursued worldwide. With regard to the time period considered in this study (2030), nuclear fusion is not able to play a role in the electricity market yet. For this reason, it will only be described comparatively briefly here.

In order to utilise nuclear fusion, fuel temperatures higher than 200 million degrees are necessary. The temperatures need to be available in a sufficiently large combustion volume in order to reach the desired fusion power. The hot centre of the plasma needs to have a minimum distance of about 1 m (in accordance with a temperature gradient of 2 million degrees/cm) to the walls of the (toroidal) combustion chamber in order to provide heat insulation. Fusion devices must necessarily be large for this reason – the small radius is about 2-3 m, the large one 6 m. Over the past decades, much progress has been made with regard to the heating-up and confinement of these hot plasmas: The triple product of density, temperature and confinement time, which is considered the most relevant plasma physics factor regarding the progress towards a fusion reactor, was improved by about five orders of magnitude between the late 1960s and the mid-1990s[1] and temperatures of up to 350 million degrees were reached. In 1991, the European fusion experiment JET (Joint European Torus) yielded fusion energy in a controlled process (1-2 MW fusion power for about 1 second [1]) for the first time in the history of mankind. Here, as well as in the large Tokamaks TFTR (USA) and JT-60U (Japan, although only with pure deuterium plasmas), plasma parameters were reached whose triple product falls short by just a factor of 6 from reactor conditions. The results reached by the European JET experiment stand out with up to 16 MW fusion power for about one second and 4-5 MW for about 4 seconds [2].

Over the last decades, the physical processes during heating-up and confinement of fusion plasmas have been understood to a large extent and it has been learnt how to optimise the performance of hot plasma. Thus, from a scientific point of view, since the end of the 1990s the way has been clear for a larger experiment which could generate reactor-scale fusion power.

9.2 The way towards a fusion reactor: ITER, DEMO, conceptual studies of reactors

The next step on the way towards fusion is the experimental reactor ITER [3], whose international collaborative construction has begun in Cadarache (southern France). Its objective is to develop relevant modes of operation and technologies necessary for the reactor. As is the case for all facilities of the “Tokamak” type, it is a machine for pulsed operation mode which, however, can also be run in stationary mode via additional systems for the so-called “non-inductive current drive”. An alternative capable of running in stationary mode without such current drive is offered by a different version of the toroidal confinement, i.e. the “Stellarator” type, for which the most advanced device is currently being installed in Greifswald, Germany. However, being smaller in size than JET, this experiment will yet be unable to generate fusion power.

---

[1] This progress equates to an average doubling within 18 months; this is comparable to Moore’s law of the semiconductor industry.

Running parallel with the ITER project, an extensive research and development programme [4] is required for fusion-specific technologies and materials. The latter are, in particular, heat-resistant “first wall” materials, as well as structural materials whose mechanical properties are capable of coping with neutron fluxes and which are to have low activation properties in order to allow them to be recycled after about one century. In order to identify materials being developed which qualify for these properties, a neutron source with a suitable fusion-like neutron energy spectrum and sufficient flux density is required for long-term tests. Currently, design and validation studies are being carried out as an international effort for such a testing facility, IFMIF (International Fusion Materials Irradiation Facility). The installation of such a facility is urgently required as development of proper materials, apart from mastering the aspects of plasma physics, will be one of the decisive factors for the success of the development of fusion power.

ITER is not yet capable of electricity generation but has been designed for testing and optimising the conditions for high performance and continuous operation of fusion facilities. This includes, apart from technological features of reactor components, the study of self-heating plasma resulting from fusion reactions, extraction of energy and ashes as well as the fuel balance in the reactor container and the fuel cycle since the tritium required for the D-T reaction needs to be bred in the reactor itself from the feedstock fuel lithium in a reaction yielding additional energy. The results of ITER, for which the first experiments generating considerable fusion power are planned for 2026 and later, are to be utilised by a fusion facility DEMO which, being a demonstration power plant, is to generate electricity from fusion energy for the first time and feed it into the grid. Since the technological essentials of a fusion reactor are already being developed through the construction of ITER, it should be possible to start the process of designing and constructing DEMO concurrently with the experiments at ITER as soon as the necessary materials have been qualified in IFMIF, which may be the case by the mid-2020s. Then, the industrial-scale development of a first generation of fusion reactors based on DEMO could be planned into which conceptual improvements, having been realised concurrently by that time, could possibly be incorporated (see also the European “Fast Track” scenario [5]).

In recent years, conceptual studies of future fusion reactors have been performed which quantify the safety and environmental properties of fusion power plants and allow for a cost estimate of electricity generation [6]. These models are based on the Tokamak principle and are aimed at power plants with a power of about 1.5 GW_e. The estimated electricity costs depend to a certain extent, as is the case with all new technologies, on the number of power plants actually built (learning curve). An essential result of these studies is that electricity costs can be expected from fusion power plants which should be able to compete with other methods of electricity generation.

A system which differs from fusion via magnetic confinement described thus far is the so-called inertial confinement fusion where small fuel pellets are being irradiated by many concentrically focused laser beams. In so doing the surface of the pellets is evaporated and the resulting recoil compresses the fuel mix inside the pellets to such a large extent that nuclear fusion is initiated. In the meantime, concepts are being pursued which are to enable ignition with less compression using additional ultra-short, extremely intense laser beams. So far, laser-based inertial confinement fusion was generally not a possibility for power generation due to a lack of lasers with sufficient efficiency and high repetition rates, but the systems were studied by the US and France for military basic research[2]. The availability of modern diode-pumped lasers makes it seem possible to generate the required light energy – several 100 kJ up to MJ per shot – with a sufficiently high efficiency in order to make the overall energy balance (90% gain) positive. Concurrently, sufficiently high repetition rates (up to 10 Hz) should become possible for the generation of 1 GW of continuous power in a laser fusion power plant. Current large-scale projects for the study of energy generation via laser fusion are being carried out in Japan, the US (“LIFE”) and the EU (“HiPER”).

[2] The largest facilities are the National Ignition Facility (Livermore, USA) which was expected to carry out the first experiments with ignited pellets in 2010, and Laser Mégajoule (Bordeaux, France) which is supposed to reach the same goal in 2014.

Proposals for so-called hybrid concepts combine nuclear fusion with nuclear fission technology for the purpose of, inter alia, transmutation of radioactive waste or the production of fuel for fission reactors. However, the advantages of nuclear fusion would mostly be lost with such systems and going by the current state of research the same purposes can be reached far more easily via genuine fission technology [7].

Fusion power plants can provide base load electricity because their operation is not subject to daily, seasonal or weather-related fluctuations. The feedstock fuels deuterium and lithium are available worldwide and their acquisition costs play only a very minor role in the economic balance of a fusion reactor[3]. The operation of fusion power plants should have a very good environmental balance: The reaction product helium is not radioactive, there are no major risks comparable to those with nuclear fission – the combustion process becomes extinct in accordance with the laws of physics in the case of an incident – and it is expected of the materials being developed that radioactive after-heat could neither lead to the destruction of the reactor nor that the final disposal of sizeable amounts of long-living radioactive materials should be necessary. Thus, in the long term, nuclear fusion has an outstanding potential to contribute to a clean, safe and reliable electricity supply on a large scale.

Notes and references

[1] *JET Team, Fusion Energy Production from a Deuterium-Tritium Plasma in the JET Tokamak*, Nucl. Fusion 32 (1992) 187

[2] Keilhacker M. et al., *High Fusion Performance from Deuterium-Tritium Plasmas in JET*, Nucl. Fusion 39 (1999) 209

[3] ITER Joint Central Team + Home Teams, *Fusion Engineering and Design* 55 (2001) 97-357

[4] *R&D Needs and Required Facilities for the Development of Fusion as an Energy Source* Report of the Fusion Facilities Review Panel, European Commission (2008) ISBN 978-92-79-10057-4, http://ec.europa.eu/research/energy/pdf/978-92-79-10057-4_en.pdf

[5] King D. et al., *Conclusions of the Fusion Fast Track Experts Meeting (King report),* Brussels (2001); and: I. Cook, N. Taylor, D. Ward, L. Baker and T. Hender, *Accelerated Development of Fusion Power*, UKAEA FUS 521 (February 2005), http://www.fusion.org.uk/techdocs/ukaea-fus-521.pdf

[6] Maisonnier, D. et al., *A Conceptual Study of Commercial Fusion Power Plants*, EFDA-RP-RE-5.0 (2004); and: D.J. Ward et al., *The economic viability of fusion power*, Fusion Engineering and Design 75-79 (2005) 1221 http://dx.doi.org/10.1016/j.fusengdes.2005.06.160

[7] See e.g. Final Report of the Fusion-Fission Research Workshop (Sept. 30 - Oct. 2, 2009) of the DOE (USA). http://web.mit.edu/fusion-fission/Hybrid_Report_Final.pdf

3 Currently, the annual worldwide demand for lithium amounts to about 122,000 tonnes LCE (Lithium Carbonate Equivalent) equating to 23,000 tonnes of metallic lithium, and the leading industrial company estimates on the basis of the technically proven recycling methods that the continental lithium resources (150 million tonnes LCE or 28 million tonnes of metallic lithium) alone are able to meet the worldwide demand (excluding nuclear fusion) for more than 1,000 years (source: Chemetal 2008). The US Geological Survey (http://www.usgs.gov/) estimates the resources and reserves to be less, i.e. about 15 million tonnes of metallic lithium. The initial fuel load of a fusion power plant is about 2,000-3,000 t LCE per GW of nominal power and the consumption is about 0.3 tonnes lithium per GW year. Thus, also for fusion lithium should not cause a bottleneck.

Part III: Transport and storage of electric energy

III.1 Grid and system aspects

1.1 Introduction

Electric energy is transported via grids which need to be designed according to the criteria of cost-effectiveness, capacity for transport, minimisation of losses as well as grid stability and operating reliability. Electricity supply thus far is based on power plants in proximity to the consumer (typically 100-200 km) with the aim of adjusting generation and local or regional consumption at any time. This local supply system is integrated in a supra-regional interconnected electricity network which mainly provides limited control and buffer functions and supply security for the rare times of power failures (outage of a power plant) but is not designed for general large power flows over long distances.

Due to the massive expansion of fluctuating wind energy supply in low load regions but also due to the desired increase of large-scale electricity trading in Europe, this concept has been approaching its limit for a long time. Therefore, two measures are urgently required: on the one hand increasing supra-regional transmission capacity significantly[1] and on the other hand making the grid intelligent (the smart grid[2]), i.e. including a temporal control of electricity consumption as a new dimension for the balancing of generation and consumption, for grid stability and CO_2 emissions as well as for the economic optimisation. In the long term, the possibility of storing a certain amount of electricity at the consumer's site (i.e. electromobility) could play a role for this new grid.

There are no suitable technologies available so far that would allow for electricity storage units to bridge a considerable share of the consumption for longer than a few hours. This lack of efficient large-scale electricity storage is a general handicap for the utilisation of fluctuating electricity sources. For this reason, the importance of an efficient European transmission grid is increasing, all the more as it can, on the one hand, compensate for the different fluctuating electricity feed-ins in different parts of Europe (e.g. by wind energy systems in various coastal and marine areas) and, on the other hand, optimise the large-scale utilisation of electricity storage possibilities, for example by utilising the Norwegian potential for hydropower by turning reservoirs into pumped storage power plants.

In Germany, but also in many other countries, the installation of new transmission lines, if licensable, requires about a decade from the planning stage to realisation and a commitment to considerable investments must be made[3]. For this reason, the development of the grid is a long-term task. Mastering it is going to be decisive for the successful restructuring of the energy system.

---

[1] The requirements of a future grid have been examined extensively in studies, amongst others, by the Deutsche Energie-Aentur (dena, German Energy Agency, dena), Netzstudie I (2005) (German only; translation: Grid Study I [2005]) and Netzstudie II (German only; translation: Grid Study II; being prepared for publication, 2010) and by the UCTE (*UTCE Transmission Development Plan* (2008 and new 2009)). The backbone of such a grid needs to be designed with high voltage direct current transmission technology.

[2] See, for example, the "E-Energy initiative" of the BMWi (German Federal Ministry of Economics and Technology): http://www.e-energy.de/

[3] B. Diekmann, K. Heinloth, *Energie* (Germany only; translation: *Energy*), Teubner (1997) p. 342 state ~70-120 € per MVA and km. H. Brakelmann quotes length-related costs of 300,000 €/km for a 110 kV dual overhead line of 30 km in length and about twice as much for an equivalent underground cable system (http://www.ets.uni-duisburg-essen.de/download/public/Freileitung_Kabel.pdf) in an expert's report commissioned by the BDEW (Bundesverband der Energie- und Wasserwirtschaft; German Association of Energy and Water Industries), *Netzverstärkungs-Trassen zur Übertragung von Windenergie: Freileitung oder Kabel?* (German only; translation: *Grid Reinforcement Lines for Transmitting Wind Energy: Overhead Lines or Cables?*), 2004

1.2 Efficient electricity transport and systems considerations

1.2–a Basic considerations

Transmission losses of electric power limit the distances which can be served well by a power plant. For alternating current, besides ohmic losses also losses due to inductive and capacitive coupling between the conductors and with the surroundings play a role which cause a phase shift between current and voltage. In order to achieve optimum compensation, a corresponding reactive power needs to be provided on the consumer side. In general, the transmission length for alternating current is limited to a few hundred km[4].

In Germany, the 18,000 km wide area transmission grid operates at 380 kV or 220 kV, the local distribution grid (level of municipal energy suppliers and industry) at 110 kV and at 20/10 kV, which, in the end, is used to provide 400 V three-phase current for the final consumer level. Power loss for common 220 kV overhead transmission lines is about 1.2% (copper) or 2% (aluminum) per 100 km plus 1% transformation losses when transforming to low voltage. At this level, further non-negligible losses occur. An additional task is the loss-afflicted distribution of the load among the different transmission paths within the grid; this is achieved by adjustment of the impedances. Overall, grid losses amount to about 6% of the net electricity generation in Germany (and also in Europe)[5].

In order to minimise power losses, the highest possible transmission voltage needs to be chosen, which however, is limited by the breakthrough voltage (30 kV/cm maximum in dry air) in connection with practicable pylon heights. Voltages of about 1 MV are thought to be possible – many 500-750 kV lines exist in practice worldwide. In Germany, the transition to voltages >380 kV for overhead transmission lines appears very difficult to realise as it is not accepted by the public due to the necessarily higher pylons and for this reason is currently not planned.

With regard to greater distances, the utilisation of high voltage direct current transmission (HVDC) is more advantageous than three-phase or alternating current transmission. HVDC is also advantageous because reactive power losses do not occur (or compensation is not necessary), utilisation of the entire cross-section of the conductive cores is not hampered by the skin effect, dielectric losses do not occur and corona discharges are of lesser importance than with regard to three-phase or alternating current. For underground and submarine power cables, which inevitably show a much higher capacitive coupling than overhead lines, HVDC is utilised even for shorter distances, e.g. for the submarine cables connecting Scandinavia with the European integrated electricity network[6]. Another advantage of the HVDC technology is that there is no frequency coupling via the transmission line i.e. there is flexibility of using transmitted power along the cable route. Individual HVDC cable routes can transmit power approaching the GW range; however, complex converter stations are required at the beginning and end of the line causing losses of about 0.8% each. The lack of frequency coupling is also advantageous in case of an incident; moreover, short disconnection times at the converter stations are possible for HVDC. Worldwide, many HVDC lines exist with lengths of about 700 km up to (currently) 2,400 km. The German industry plays a leading role in the further development of state of the art HVDC technology.

---

4 Oil-paper insulated underground cables are frequently used for three-phase or alternating current transmission in densely populated areas. They are expensive and have considerably higher losses than overhead lines due to the high capacitive coupling between the conductors – their lengths, therefore, are limited to well below 100 km.

5 Source: Monthly report on electricity and heat generation of electricity generating facilities for general supply, Statistisches Bundesamt (German Federal Statistical Office), figures for second and third quarter 2009.

6 One example is the 580 km long and up to 420 m deep NorNed cable route connecting Feda (Norway) and Eemshaven (The Netherlands) which went into operation in 2008. Here, two-core copper cables (2 x 790 mm^2) at ±450 kV with a transmission capacity of 700 MW are utilised. Monopolar submarine cables (the return conductor is the seawater) are also employed at times for marine routes.

Altogether, technological solutions for an efficient future wide area, grid are available, even though further important improvements are possible (e.g. the transition from conventional HVDC thyristor technology to IGBT electronics[7]).

1.2–b Problems and goals

With regard to the building up of decentralised renewable energy systems, wind energy poses the biggest problems for the grid design[8]. The German government intends to extend wind energy utilisation in the North and Baltic Seas up to 20-25 GW installed power by 2025/30, which is comparable to the capacity installed on land near the coast. This way, an overall potential of up to 55 GW of fluctuating electricity generation is being created in Northern Germany – a region with mostly low electricity demand. This equates to nearly half of Germany's current total gross capacity for electricity generation (currently 121 GW), and at nearly the same level back-up power needs to be available in the grid as the secured wind power only amounts to 5-10% of the nominal power[9]. The contribution of fluctuating sources to the reliability of supply is therefore very small and the feed-in priority legally guaranteed for these sources considerably increases the demands on the grid. Massive investments into the grid infrastructure are necessary in order to cope with predictable, but also, and particularly, with unpredictable load variations occurring on a thus far unknown scale[10]. Wind energy facilities built prior to 2003/4, for example, disconnect themselves from the grid at voltage drops >20% and in doing so amplify the critical situation. Analyses show[11] that already in 2003 the reliability of the grid could no longer be guaranteed according to the defined standards: Certain errors in the transmission grid which could not be precluded or the sudden failure of a large conventional power plant could have caused a critical grid state with wide-ranging voltage drops which eventually would have put too much strain on the back-up reserve of 3 GW of the European integrated electricity grid – resulting in a large-scale grid breakdown.

Improvements with regard to new wind energy facilities have, meanwhile, been introduced[12], but the retrofitting or repowering of old facilities is perhaps also necessary. In view of the planned shutting down of nuclear power plants, it is expected that the increase in the fluctuating feed-in will result in the grid stability approaching an increasingly critical state by 2015 at the latest. Another issue is that such an amount of electricity must be transmitted to neighbouring countries when strong winds occur in low load situations (at night, during the weekend) that it exceeds the specifications of cross-border transmission lines. Thus, the issue becomes a European one. In the long term, it will be inevitable to give up the feed-in priority of wind generated electricity legally guaranteed as per the EEG and to include the powering down of wind energy facilities during load-critical situations into the available adjustment possibilities. The same applies to photovoltaics.

---

[7] Insulated gate bipolar transistor technology is increasingly gaining importance in the field of power electronics and high voltage transformers.

[8] The same problems apply to photovoltaics, albeit to a lesser extent, as it will probably always provide less energy than wind energy facilities in Germany.

[9] Source: Netzstudie I (German only; translation: Grid Study I) by DENA (German Energy Agency). For the purpose of comparison: The secured power of the power plant fleet consisting of hard coal, lignite and nuclear power plants, oil/gas combined facilities, biomass and geothermal power plants as well as pumped storage power plants is about 86-93% of the nominal power, that of gas turbines is 42% and that of photovoltaics is 1%. Source: DENA (German Energy Agency) or TU Munich, Lehrstuhl für Energiewirtschaft und Anwendungstechnik (Chair of Energy Economy and Application Technology, TU Munich), 2008, citing H. Krüger, DENA.

[10] Whereas the failure of one power plant, that is of a power of up to one GW, could be expected in scenarios of incidents so far, now short-term power fluctuations, higher by up to one order of magnitude, can occur. It must also be noted that higher investments into the back-up power plant fleet are necessary if it is to be built in such a way as to avoid CO_2 emissions and if a sufficiently efficient wide-area grid should not be realised (in time).

[11] See Netzstudie I (German only; translation: Grid Study I) by DENA (German Energy Agency)

[12] Newer wind energy facilities must stay connected to the grid up to voltage drops >80% or are only permitted to disconnect from the grid with delay.

1.2–c System considerations and need for action

The grid needs to be adjusted to the new conditions arising from the extension of the fluctuating energy systems and the desired Europe-wide electricity trade. There is an urgent need for action with regard to the retrofitting of old wind energy facilities, the adaptation to grid connection conditions and particularly to meeting the legal requirements with regard to planning and licensing of the extension of the grid. Furthermore, the inclusion of wind energy facilities in the grid operation control (feed-in management, contributing to providing controlling power, improving grid support for critical situations) should be made legally possible and technologically realised. Eventually, the extension of the European integrated electricity network will have to be enforced. Possibilities for the realisation of large-scale storage facilities need to be explored further.

In this context, it is advisable to consider potential scenarios in which the back-up power necessary for high reliability of supply is mostly not being provided by conventional power plants, but by a mix of renewable energy systems. Such a mix would be dominated by the strongly fluctuating wind power in particular[13] in (Northern) Germany up until 2050 and probably beyond, even if in the long term the largest possible contribution of controllable, non-fluctuating hydropower, biomass and geothermal power plants could be realised. In order to guarantee the necessary supply reliability, two extreme possibilities may be discussed: Firstly, either the grid capacity for electricity transmission to the considered (greater) region would, in such scenarios, need to be dimensioned in such a way that other regions would be able to meet nearly the entire electricity demand of the considered region at weak wind conditions, or, secondly, in the other extreme, the capacity of wind energy facilities would need to be increased in such a way as to guarantee the supply of the region even at weak wind conditions which would mean an enormous surplus capacity of wind turbines. Under strong wind conditions, this would, of course, lead to a correspondingly large surplus production of electricity (a phenomenon already occurring at times at the current state of installation and which has already led to negative electricity prices). If, for example, 50% of the German grid peak load is to be guaranteed at all times by means of wind power, the surplus capacity would need to amount to 17 times[14] this grid peak load under strong wind conditions if the current supply reliability is to be maintained[15]. This would obviously require enormous investments into the wind energy facilities but also into the transmission grid since the largest share of the surplus electricity would need to be transmitted out of the region of its generation if there are neither sufficient electricity storage facilities (which will most likely be the case for a long time) nor loads adjustable to the fluctuating wind supply such as hydrogen production[16] or electric space heating or cooling (heat pump)[17]. It would not be sensible to “ditch” the surplus (i.e. not to generate it) by putting the turbine blades into the no load position. With an increasing share of non-fluctuating electricity generating systems and, if technologically realisable, considerably expanded large-scale electricity storage facilities, there could

[13] In 2006/7, the installed wind capacity was 21,500 MW; the generated wind power was 4,430 MW on average and fluctuated between a maximum of about 18,000 MW (over several hours about 15 March 2007) and a minimum of 380 MW (over the period from 6 June to 10 June 2006). Periods of weak wind (generation of less than 5% of the installed wind capacity) roughly comprised an accumulated 50-60 days, i.e. about 15% of the considered period (1.4.2006–31.3.2007, data provided by Deutsche ÜNB (Übertragungsnetzbetreiber; German Transmission System Operator [TSO]).

[14] An assumed future grid peak load in Germany of about 87,500 MW and a share of 40,000 MW of wind power would require a 17-fold surplus capacity, i.e. for every 1,000 MW, 17,000 MW wind energy facilities would be needed. Source: Prof. Th. Hartkopf, TU Darmstadt.

[15] For the purpose of comparison: This factor is about 1.3–1.4 in the conventional energy system. For instance, on 15.12.2005, the date of the highest peak load (of 76.7 GW) for that year, the overall capacity of the German power plants was 110.4 GW. Excluding the internally required power of the power plant fleet, failures, shut downs for revision, reserve for system operations, the guaranteed power was 82.7 GW. Source: DENA (German Energy Agency).

[16] This hydrogen can be considered a chemical storage device for electric energy and could thus be utilised, for example, in the transportation sector for fuel cell electric drives or could also be pumped into the natural gas supply grid and thus help to reduce the consumption of fossil natural gas. (Source: see footnote 14).

[17] The occasionally suggested utilisation of surplus electricity for (night) storage heating is convenient only if the share of carbon-free electricity generation will become large enough, even in times of (predominantly) minor electricity generation from wind energy, to make those heating systems climate-politically acceptable. Other storage methods (e.g. compressed air energy storage) are neither technologically nor economically in view (see chapter III.2).

be a downward trend of the surplus factor which however, will probably still remain impressive. The reality will be somewhere between these extremes. However, if fluctuating wind energy (and photovoltaics) really ought to provide a reliable share of the electricity supply, this would require the provision of a surplus generating capacity which must be several times higher than actually required by the grid peak load due to consumption - and a corresponding grid enhancement so as to make this surplus power available over large distances to electricity trade and hence to other consumers.

It can be expected that the share of fluctuating electricity feed-in – currently, the installed wind power already amounts to roughly about 30 GW[18] – will increase considerably over the next two decades. It is all the more important, therefore, to allow for significant contributions from the European integrated electricity network (e.g. from southern solar thermal energy[19] or other power plants) to ensure reliability of supply. Investments into a strong trans-European high voltage direct current transmission grid thus gain enormous importance. Also, concepts should be realised which mitigate the issue by a certain balancing of electricity consumption (smart grid) to the fluctuating electricity generation.

1.2–d Costs

So far, cost assessments were based on the assumption that the grid capacity was required to meet the breakdown of a large power plant in addition to the maximum consumption in a certain region, which usually meant a comparatively moderate increase in power in the transmission lines (e.g. by some ten percent). Since the statistically proven wind power (in relation to the defined supply security), as already discussed, only amounts to 5-10% of the nominal power[20], the transmission capacity to and from other regions of generation will need to be extended in the future.

Furthermore, according to calculations by DENA, about 15-20% of the installed wind power must be kept operational as a back-up reserve in other power plants under no load operation conditions for providing positive or negative *controlling power* for minutes and hours. With regard to the investments into new power plants this situation is currently causing a shift to (natural gas) facilities requiring less capital investment but causing higher specific fuel costs. However, the overall fuel costs are lower than costs for conventional operation due to the limited time of capacity utilisation. Overall, however, the additional costs caused by expensive electricity from wind significantly exceed the savings from fuel and investments in new power plant installations. The generated electricity thus becomes more expensive.

Considerable costs are also caused by the situation described above: the wind capacity and the grid need to be expanded, possibly far beyond the grid peak load necessary due to consumption. About 20 billion € will need to be invested into the expansion of the grid with regard to the (three-phase) maximum voltage level (220/380 kV) in Germany by 2020[21]. Compensations as per the EEG are intended to be used to finance the additionally necessary connection of the wind farms to the network connection point.

[18] Source: Netzstudie (German only; translation: Grid Study) by DENA (German Energy Agency)

[19] See chapter II.5.3

[20] The guaranteed power of hard coal, lignite and nuclear power plants, oil/gas combined facilities, biomass and geothermal power plants is about 86-93% of the nominal power, that of gas turbines is 42% and that of photovoltaics is 1% (source: DENA; German Energy Agency).

[21] Source: DENA (German Energy Agency). Summary of the essential results of the dena study by the project management group (23 February 2005). Costs of 30 billion € are estimated for the extension of the integrated electricity network of all littoral states for utilising wind energy generated from the North Sea (source: German newspaper “Süddeutsche Zeitung”, p.17, 5 January 2010). The overall investments into the European electricity system (electricity generation and networks), in accordance with the goals of climate protection and supply security, are estimated to amount to roughly 700 billion € each for the coming decade as well as the subsequent one, about 40% of this sums will be required for extending the grid and a similarly large share for renewable energy sources (source: IEA [International Energy Agency] citing German newspaper “Die Zeit”, 29 April 2010, p.23/24).

1.3 Smart grid

In order to match daily load fluctuations with electricity generation as well as possible, day and night tariffs including separate electricity metres have long been introduced in many areas for the final consumers. Now worldwide efforts are being made to regulate consumption better via a *smart grid*, i.e. by making it possible to bi-directionally regulate the entire chain from electricity generation to distribution to the consumer by means of information and communication technology from the electricity provider or the transmission system operator. Not only is load balancing intended by the providers[22] but they also hope to shift (as large) a share of final consumption (as possible) to high-supply times with low electricity generation costs by directly regulating consumption or offering incentives. This, of course, results in a reduction of the amounts of electricity to be provided by peak load power plants, which can also have a positive effect on CO_2 emissions.

The *smart grid* is mainly advertised as allowing the final consumer to regulate and reduce electricity consumption better. Some of these options already exist today, however: Many washing machines and dryers, for example, have a time-shift function and many other devices can be operated using inexpensive clock timers. Of course, an intelligent adjustment of consumption to the actual electricity supply would provide additional avenues of optimisation. It is doubtful, however, that a shift in consumption will be possible for more than a few hours for most energy-intensive applications. As it is, private consumers only have relatively limited options to shift consumption to low load times (e.g. the early hours of the morning) beyond what is already possible today in order to avoid higher electricity costs.

Concepts for a *smart grid* allowing for the inclusion of regulable consumption in the overall optimisation by including an exchange of information with the consumer are being discussed worldwide. It is questionable whether *smart grids* will actually lead to considerable energy and CO_2 savings which cannot be achieved by means of economic incentives or regulatory measures since they are mainly connected to consumer habits.

In view of the extension of electromobility, the utilisation of the storage units of electric cars as buffers in the grid for matching electricity supply with electricity consumption is being discussed (see chapter I.3 on electromobility). Current lead accumulators used exclusively as starter batteries are not suited for this task (limited charging/discharging cycle, much too limited a capacity). Furthermore, there is no infrastructure to allow most of the vehicles to connect to the grid since they are not parked in garages but on the side of the road. Should vehicle batteries be available in large numbers and with a much higher capacity and number of charging/discharging cycles in electric cars, they could, given an adequate infrastructure, be charged in low load times during the night and be utilised as storage units during the day if they are only used, for example, for driving to and from work in the morning and evening. This would, however, considerably restrict the car holder's flexibility. To what an extent such a concept would be accepted, even if a sufficient number of "charging stations" (perhaps for exchanging batteries) were available, cannot be predicted yet.

In summary it can be assumed that the concept of the *smart grid* will certainly be realised soon as it opens up attractive possibilities for electricity providers and is politically appealing as well. In a first step, *smart metering* is going to be introduced in Germany in the near future, supported by legal measures[23]. It is apparent with regard to private households that individual consumer habits need to be changed by the *smart*

[22] This applies particularly to companies which are in direct contact with the final consumers (DSO = distribution system operators) and only in the second place to the transmission system operators (TSO) which already have extensive information systems for grid and load optimisation. The US smart grid market is estimated to be worth 200 billion US$ by 2015. These attractive investments are expected to be the overwhelming share of the total investment volume of the utilities (source: Dayton Business Journal, 29 December 2009).

[23] For example, the installation of intelligent electricity metres is legally required in Germany since 2010.

grid if a significant decrease in consumption and thus CO_2 savings are actually to be achieved. The *smart grid* also opens up an arena for critical considerations regarding data protection and privacy matters.

III.2 Electricity storage methods

2.1 Introduction

The share of regenerative energy sources of the total electricity generation has been steadily increasing in Germany in recent years. Wind energy claims the lion share of the increase and will continue to grow and thus considerably dominate the other renewable energy sources in the near future.

The feed-in amount of wind power, however, strongly fluctuates (the same applies to the currently still relatively unimportant photovoltaics). This fluctuating feed-in is met by a fluctuating use on the consumer side – the difference needs to be compensated for by power plants controllable at short notice and by storage facilities (primary control in the millisecond range, secondary control in the minute range). The profits from this so-called control energy are subject to strong fluctuations themselves and reflected as an extremely volatile price index on the EEX spot market. For individual hours, the spot market price reaches four times the amount of the average price, for other hours of extreme electricity surplus even negative prices can be achieved. The reason is that control energy can, in part, only be provided for by comparatively slowly adjustable power plant power and the fluctuations can thus be compensated for only laboriously (the forecast of wind energy feed-in is already unreliable on the minute and hour scale and shows significant deviations from the actually occurring feed-in amount in the one-day or several-day forecasts).

Therefore, electricity storage will play an increasingly important role in the future as part of the grid management and will require the integration of as efficient as possible, decentralised storage units for electric energy[1]. Due to the strong volatility of the electricity price even low-efficiency storage methods can, in certain circumstances, be cost-effective. The trend, however, will be a reduction of this strong volatility due to the increasing integration of storage units and the introduction of load management instruments; hence even now, only sufficiently effective storage methods should be developed further.

Possible electricity storage units are:

mechanical storage units
• flywheel

hydraulic storage units
• pumped storage power plant
• compressed air storage

electric storage units
• superconducting coils
• double-layer capacitors

electrochemical storage units
• batteries
• redox-flow-cells
• hydrogen-electrolysis (+ fuel cells)

---

[1] For more details see, for example, R. Schlögl und F. Schüth, *Transport- und Speicherformen für Energie* (German only; translation: *Types of Energy Transmission and Storage*) in *Die Zukunft der Energie* (German only; translation: *The Future of Energy*), edited by P. Gruss and F. Schüth, C. H. Beck, Munich 2008, p.246-281

In the same category as direct electricity storage one has to see heat storage in solar thermal power plants which levels electricity generation even into the night and, thus, eventually replaces electricity storage. Therefore, the latter will also be discussed in this chapter.

All of these storage technologies differ significantly in parts with regard to their relevant parameters. Some are applied only as short-term storage units for load adjustment, others are utilised as long-term storage units (hours to months). The specific costs as well as the degree of technological development of the various methods also differ significantly. Therefore, a short overview of the methods and framework conditions of the various technologies will be given in the following chapter. A table (Tab. 1) summarising and comparing the different storage methods can be found at the end of this chapter (subchapter 2.6).

2.2 Mechanical storage units: flywheel

In flywheel storage units, electric energy is transformed into rotational energy of an inert mass via an electric motor and can be extracted as needed via a generator by decelerating the flywheel. Conventional systems utilise large, heavy steel rotors which are supported by mechanical bearings. Due to the relatively low tensile strength of steel the rotational speeds are limited to about 5,000 rpm. Modern systems are made of carbon fiber composite materials of considerably greater tensile strength whose theoretical energy density is higher by one order of magnitude and which are able to withstand rotational speeds of up to 100,000 rpm. The main advantage of flywheel storage units is their high efficiency of above 90% with regard to short-term storage. However, flywheel storage units are unsuitable for long-term storage due to their high loss rate (1-10% / hour). Flywheel storage units are technically mature, commercially available and will continue to play a large role with regard to power storage and emergency power supply in the range of minutes.

2.3 Hydraulic storage units

In **pumped storage power plants**, at times of surplus electricity, water is pumped up to a reservoir (natural lake or artificial basin), which is located as high up as possible, and, if required, is carried via penstocks to the turbines into a water basin located below. Pump and turbine losses (including motor/generator) are about 10% each, resulting in an overall efficiency of modern pumped storage power plants of about 75-85%. They are capable of rapid adjustments, the start-up time (both for the power plant and pumping operation) is usually about 1 minute. After that, they are typically capable of generating electricity in full load for several hours. For this reason, they are particularly well suited to operating as load-following power plants for day/night compensation; in principle, seasonal storage is also possible due to their very small storage losses (evaporation or seepage of water). Currently, there are about 30 pumped storage power plants with a power of nearly 7,000 MW and an overall capacity of 40,000 MWh in Germany, making pumped storage the only large-scale storage technology presently existing. A comparison of the overall capacity with the installed wind power (2010: about 30,000 MW) shows, however, that this capacity, too, could compensate for only about one hour of calm. Increasing the number of pumped storage power plants, however, is very difficult because of the various demands on possible locations (large differences in altitude, large storage volume, compatibility with environmental and landscape requirements).

In **compressed air energy storage** (CAES) power plants, combustion air for a gas turbine is compressed by means of an electric compressor and is stored in large underground caverns for long periods of time. If required, this air can be utilised as combustion air for a conventional gas turbine; however, it only needs to be heated up and not compressed further by the fossil fuel. This increases the efficiency of the genuine gas turbine considerably. CAES units, thus, are, in principle, nothing but gas turbines in which the compression of the combustion air is separated with regard to time and plant-engineering from utilisation in the turbines.

The only CAES power plant in Germany (Huntdorf, built in 1978, 290 MW, 310,000 m^3 storage volume) has an efficiency of 42% which could be increased, in principle, to slightly above 50% by an optimised system design. Overall, however, the efficiency is rather low due to the large heat losses of the compressed air.

In order to bypass the heat loss of the CAES technology, advanced **adiabatic compressed air energy storage** (AA-CAES) units are being developed which buffer the compression heat and utilise it to heat up the expanded air. This way, the compressed air can be utilised directly, without gas-heating; the overall efficiency can reach values of about 70%. This concept has not been tested yet, however. The main difficulty, naturally, is the huge heat storage facility which needs to operate at storage temperatures of several hundred degrees Celsius. Materials such as porous ceramics or concrete are suitable. Various system configurations are currently being tested, e.g. in a project subsidised by the EU. First power plants could be operational by 2020 at the earliest.

2.4 Electric storage units: superconducting coils and double-layer capacitors

“Electrically” storing electric energy as directly as possible seems to be a very effective approach at first glance since losses are avoided during the transformation into other forms of energy (mechanical energy, chemical energy). The main storage technologies are **superconducting coils** (SMES) which store energy in the magnetic field of the coils as well as **double-layer capacitors** (supercaps, ultracaps) which store energy in the electric field. Both approaches – allthough technologically very different –have a very high charging/discharging efficiency of above 95% as well as an unfortunately relatively high loss rate of above 10% per day in common. Both storage methods are infinitely cyclable, system costs are immensely high, however. They exceed the specific cost (per kilowatt hour) of a pumped storage power plant by about three orders of magnitude. For this reason, electric storage units are unsuited for large-scale network management – their main application (in the stationary field) is going to be emergency power supply in the millisecond range as a result of their short response times and high power density. Furthermore, supercaps are going to play an increasing role as power buffers in electric vehicles, i.e. with regard to electromobility.

2.5 Electrochemical storage units

When electrochemical storage units are charged, electrons are moved from one reactant to the other by an external force, i.e. one substance donates electrons (oxidation) and another accepts them (reduction). This results in a change of the energy state of the whole system and a concurrently occurring externally measureable cell voltage. During discharge, this process, driven by the voltage difference, runs on its own in reverse direction. The two reaction zones (anode and cathode) are connected by an electronically isolated, but ion conducting electrolyte which closes the current loop. The maximum energy density (in Wh/kg) is mainly governed by the mass of the active reactants. In principle, therefore, electrochemical storage units based on lithium (M=3) promise much higher energy densities than lead accumulators (M=207).

Electrochemical energy storage methods are an important focus of current research worldwide, both in basic research at universities and in industrial research. As a result, various and very different systems are being tested and optimised.

Lead accumulators have been steadily further developed for over 100 years and remain one of the most reliable electrochemical storage devices to this day. All reactants (Pb, PbO_2, $PbSO_4$) are solids and remain bound to the electrode plates which are immersed in diluted sulfuric acid. During discharge, sulfuric acid is used up meaning that the charging state can be determined directly from the acid content of the electrolyte. Lead accumulators are characterised mainly by robustness, large numbers of cycles and very low loss rates.

Furthermore, they have another advantage: They are very inexpensive compared to other electrochemical storage devices. Their main disadvantage is their enormous weight, which however, is only of importance with regard to mobile applications. Several electric large-scale lead accumulator-based storage units are in operation worldwide, the largest one with 40 MWh is located in California.

For this reason, alternatives to the lead accumulator are being searched for intensely, particularly with regard to mobile application. Currently, mainly **nickel-metal hydrid accumulators** are used (e.g. by the Toyota Prius) for this purpose (cf. chapter I.3). They have existed for 20 years as a further development of Ni-hydrogen cells using a hydrogen compound (metal hydrid) for storage as opposed to the precursory cells which stored hydrogen as a gas. This lessens the achievable energy density, however. A problem in particular with regard to mobile application at below zero temperatures is the liquid electrolyte. A big advantage compared to e.g. lithium batteries is, however, that NiMH accumulators do not have major safety issues. They do not contain any toxic substances.

Lithium is the lightest metal and, in principle, thus allows for the production of batteries with a very high energy density. On the other hand, however, it is very reactive and thus poses a safety problem. Only due to the development of graphite intercalation anodes (as a further development of cells with a metallic lithium anode) could accumulators suitable for practical use be built. The safety of Li-ion cells remains an important issue to this day, however. Lithium-ion batteries need to be operated very carefully, they do not tolerate deep discharging, over-charging or high temperatures. Above about 70°C there is the danger of an irreversible thermal release of the stored energy. In larger multiple-cell arrangements, all cells currently still need to be monitored individually with a load protection device. Lithium-polymer accumulators offer a higher degree of safety: Instead of the liquid electrolyte, a solid polymer is used here. Currently, the number of cycles of the latter cells is only about half the number of the cycles of the former. Further improved cells with a higher capacity (currently limited by the cathode) and better operating behaviour are expected in the coming years due to the immense research efforts undertaken worldwide.

With regard to the achievable storage density the class of **metal-air batteries** has considerable potential. Here, the active substance at the cathode is ambient oxygen from the neighborhood which therefore does not contribute to the cell weight. The main disadvantage is that most systems cannot be electrically recharged. It is possible, however, to extract the spent metal from the anode, reduce it separately by electrolysis and recycle it. An efficiency of 60% for the whole cycle has been proven already.

The zinc-air battery has been developed furthest; however, systems based on e.g. aluminum or lithium are being studied as well. Zinc-air batteries are characterised by an excellent energy density and low costs and are thus suitable for mobile applications, too. The use of 150 kWh systems in electric vehicles of e.g. the Deutsche Bundespost has been tested successfully.

The beginning of the **high temperature sodium battery** was the discovery of a ceramic material (b-aluminumoxide) which, from about 300°C, has a very good conductivity for Na+ ions but is a perfect electronic isolator and at the same time leak-tight for all other substances. Sulfur is usually used as a cathode material. Both sulfur and sodium are liquid at operating temperature. Sodium-sulfur batteries are characterised by high energy density, high efficiency, and high cycle stability. Self-discharge is virtually absent, but thermal losses need to be taken into account for longer off-times. The materials used are relatively inexpensive and non-toxic. A disadvantage is the high corrosivity of liquid sodium and the high operating temperature (thermal cycling must be avoided as well), which restricts the utilisation of these batteries to large-scale stationary installations (batteries for network stabilisation with powers up to 20 MW are used primarily in Japan). The development of batteries for mobile use has been mostly discontinued.

A variant of the NaS battery is the so-called ZEBRA battery. NiCl is used here as the cathode material instead of sulfur. This battery is characterised by a simpler technical design as well as by advantages with regard to various safety issues, making mobile use seem possible here as well. Due to industrial property rights, this system is being developed further by only one company in the world.

Redox-flow batteries are open systems in which all redox species exist in solution, are stored in separate tanks and are pumped, together with the electrolytes, through the actual electrochemical cell during the charging and discharging process. In so doing, cell power and stored energy are decoupled. The maximum theoretical energy density results from the solubility limit of the active ions in the electrolyte and amounts to 25 Wh/kg for e.g. the pure vanadium system. The electrolyte is almost infinitely recyclable, flow batteries are widely tolerant of deep and partial discharges and can be charged and discharged at any rate.

Vanadium-flow batteries have been developed to commercial market maturity, but are used only in a small number of units worldwide, amongst other things for compensating fluctuations in wind energy facilities. Apart from the pure vanadium system, other systems have also been developed (e.g. Fe/Cr, V/Br). Advantages are a possibly higher energy density and possibly less expensive materials. The main disadvantage of these systems, however, is that they degrade quickly due to the crossover through the separator, and the number of cycles is thereby reduced. In principle, flow batteries have a high potential for cost reduction due to the possible scalability of the facilities and the long lifetime.

Another open electrochemical system relates to **hydrogen fuel cells** operating in combination with upstream electrolysers. Alkaline electrolysers have been commercially available in units of between a few Watt and about 1 MW for decades. Typical efficiencies are between 60 and 75%. Conventional systems operate at pressures of several mbar, further developments are pressurised electrolysers operating at about 15-30 bar. This is advantageous with regard to storing the produced hydrogen. Perhaps compression can be discarded altogether or at least one compression stage can be saved. Improvements are to be expected with regard to efficiency, power density (and thus the costs), primarily due to the development of new cathode and anode materials. Further methods are PEM electrolysers or high temperature electrolysers (based on SOFC technology) which, however, are not in large-scale use yet.

For the purpose of re-conversion, hydrogen can, in principle, be utilised in various processes, e.g. in conventional thermal power plants. For the whole system including an electrolyser, it is the realisation in PEM fuel cells that is mainly being discussed (for larger storage units high temperature SOFC fuel cells are used in addition). The thermodynamic efficiency of both systems is comparatively high. Due to the excess voltage at the electrodes and ohmic losses overall efficiencies of about 50% are reached in a real system. Apart from the high costs, PEM systems, however, currently still suffer from high degradation (by now, typical lifetimes have increased from 1,000 h to over 5,000 h).

Thus, an overall efficiency of about 70% * 50% = 35% is reached by the whole hydrogen system. For this reason, these systems are uninteresting in terms of energy. The only advantage is that, in principle, virtually lossless long-term storage as well as transport over long distances is possible.

2.6 Summary of electricity storage units

Table 1 provides a summary of the parameters of the electric storage units discussed above which are most important for the application in the field of network management. It is obvious that pumped storage power plants represent the best system in view of economics (cost-effectiveness) and technology (cycles, efficiency, loss rate). Only the energy density is very low here which in the end results in the enormous area that is required; for this reason – as already discussed above – additional pumped storage units are difficult to realise in Germany. Compressed air energy storage (CAES) units cause significantly higher costs and should be designed only with integrated heat storage (AA-CAES) devices for reasons of efficiency. These systems are still under development, however. Flywheels and direct electric storage units (SMES, supercaps) are only a short-term power reserve option due to the enormous costs. All electrochemical storage units are expensive and therefore economically difficult to realise under current conditions. Redox-flow batteries, which are already being used in some installations for balancing the electricity output of wind energy facilities and are capable of operating virtually lossless, have the greatest potential for development (including cost reduction).

	Wh/kg	Euro/kWh	# Cycles	Efficiency	Loss rate
Flyweel, steel	5	3000	unknown	90 %	10 % / hour
Flywheel, CF	100	5000	unknown	90 %	1 % / hour
Pumped storage	1	50	unknown	80 %	0 %
CAES	-	400	unknown	50 %	0 %
AA-CAES	-	800	unknown	70 %	0 %
SMES	3	100000	unknown	95 %	10 % / day
Supercaps	5	10000	unknown	95 %	10 % / day
Lead acid	40	200	2000	85 %	0.1 % / day
Nickel-MH	80	2000	1000	70 %	1 % / day
Lithium ions	130	1000	2000	90 %	0.2 % / day
Zinc-air	200	30	-	60 %	0 %
Sodium-sulfur	110	300	3000	85 %	10 % / day
Vanadium-flow	25	500	unknown	75 %	0 %

Tab. 1: Overview of the most important parameters of the various electricity storage units

2.7 Heat storage units for solar thermal power plants

Just as important as the direct storage of the regeneratively produced, strongly fluctuating electricity supply are solutions which already achieve a balancing of electricity generation by suitable measures on the generating side. In this context, heat storage units for solar thermal power plants will be discussed in this chapter on electric storage units. In solar thermal power plants, a primary heat carrier is heated up to temperatures of up to about 1,000°C depending on the applied technology (parabolic troughs, solar towers). In a heat exchanger, the thermal energy (generated only during day-time) is transferred to a secondary steam circuit which drives a steam turbine. By employing additional heat storage units in the system, the turbines could also be supplied during the night, which would make a continuous 24h operation (not been realised yet) possible in principle.

Typical parameters of the primary heat carriers of the most important systems are:

heat transfer oil	400°C	15 bar
water/steam	400°C	100 bar
air	1,000°C	1 bar

In principle, the primary heat carriers can also be stored directly in large tanks. The heat capacity of air (and, with restrictions, also of steam), however, is so low that it makes the heat transfer onto another storage medium mandatory. For reasons of cost-effectiveness, a less expensive storage medium than heat transfer oil is usually used. The most promising systems developed so far are:

Molten salt: For instance, the Spanish Andasol power plants use a eutectic mixture of 60% $NaNO_3$ and 40% KNO_3. These salts have a low melting point (222°C), are available for large-scale use and relatively inexpensive (fertilisers). Sensitive heat can be stored with a heat capacity of 1.6 kJ/kg K; the useable temperature range for storing sensitive heat has a lower boundary due to the melting point and an upper boundary due to the temperature of the primary heat carrier. The main disadvantage is that the salt mixture solidifies below 222°C and thus needs to be heated permanently in order to avoid the system‘s destruction.

Concrete: Applying tube bundle heat exchangers in a solid conrete matrix, sensitive heat is stored at a temperature range from 200 up to above 500°C in the (relatively inexpensive) solid substance concrete. Its heat capacity is 1.3 kJ/kg K. The main difficulty is the (free or chemically bound) residual water in the concrete which needs to be driven out of the system during the first cycles. Therefore, sufficient vapour permeability needs to be provided. Furthermore, the different heat expansion of the tubes needs to be taken into account when compared to concrete. For this reason, a certain amount of free moving space of the tubes needs to be provided for without hampering the heat transport.

Sand storage units: A storage concept is being developed particularly for solar towers where hot air of about 1,000°C is transferring its heat energy to the solid material sand inside a counterflow heat exchanger. That is, the quasi-fluid storage material sand is conveyed and stored in a reserve container after being heated up. In another heat exchanger, the heat can be re-extracted from the sand. The costs for this storage material are very low, but the investment costs are much higher due to the complicated set-up of the system.

PCM storage units: During phase change (e.g. transition solid-fluid) a lot of thermal energy is stored in a narrow temperature interval. PCM (phase change materials) storage units are thus ideal storage devices for the water/heat systems which contain the main share of thermal energy in the phase transition. In this regard, the transition temperatures on the primary and secondary side need to be adjusted, however (e.g. via the operating pressure in the steam circuit).

Nitrate salts (also used in sensitive heat storage units) and their eutectics, e.g. $NaNO_3$ (melting point 306°C) or KNO_3 (334°C), are especially suited as phase change materials in the temperature range between 130°C and 340°C. The main difficulty here is the low thermal conductivity, particularly in the solid phase. Sandwich structures made of thermal conductive materials (graphite or metals) and storage material are being studied.

Apart from storing the enthalpy of condensation in the steam circuit, PCM storage units are, in principle, also suited for storing sensitive heat of e.g. heat transfer oils. Particularly promising here are cascades of PCM storage units with different melting temperatures which are passed through serially, thus facilitating a significantly higher storage density as compared to purely sensitive storage units.

2.8 Summary and outlook

Thermal storage units in solar thermal power plants will contribute significantly to balancing the fluctuating supply of regeneratively produced electric energy. The technology is already available; in addition, various approaches to further developments (with regard to storage density, efficiency and costs) exist.

Currently, only pumped storage power plants are available for direct electricity storage on a scale that it is relevant for the load management of the entire electricity network, whereby it must be expected that a relevant expansion is not possible. Further developments of compressed air energy storage units with integrated heat storage units (AA-CAES) have the potential to become relevant for large-scale application. System costs are significantly higher here and the issue of suitable locations needs yet to be studied in more detail. Electrochemical storage units are usually too expensive (due to a limited number of cycles), making their application for network management seem rather questionable, at least from an economic point of view.

Intelligent network management, therefore, should always take priority over any method of electricity storage, which always includes losses. This comprises quickly controllable power plants (e.g. gas turbines) on the producer side as well as load management on the consumer side. A time-adjusted operation of these systems, particularly in systems which provide electricity via thermal energy, can make electricity storage in the form of heat and cold highly efficient in the end.

Towards low CO_2 emission

Despite an increase in electricity productivity the demand for electricity has continued in recent years to increase in Germany[1], which can be regarded as a typical representative of western industrial nations (OECD countries). The advantageous properties of electric energy afford many reasons why this trend will continue in the medium and long-term future and will probably even gain momentum. Examples of extended and additional future applications of electricity were extensively discussed in the first part of this study; of these, electrification of traffic (i.e. electromobility) and heating of thermally renovated buildings via electric heat pumps could gain great importance.

A climate-friendly supply of electricity – and energy in general – meeting the worldwide increasing demand needs to be examined and discussed within the context of an integrated energy and climate policy concept. The worldwide supply of electricity will continue to rest on three pillars for a long time: first, fossil primary energy carriers (mainly coal and gas); second, renewable energy systems (initially primarily wind, hydro power and biomass, later geothermal energy, concentrating solar heat and – in Germany to a lesser extent – photovoltaics); and third, nuclear fission energy. From the second half of this century onwards, nuclear fusion energy could possibly begin to play a significant role. These energy systems need to be analysed with regard to the most important basic requirements, which include security of supply, economic efficiency and sustainability in particular.

This analysis is prominently featured in the second part of this study. It confirms what had been said in the 2005 study by the German Physical Society: At least during the first half of this century there will be no ideal solution for any of these three pillars to support carbon-free electricity and energy supply alone. This also applies to renewable energy systems[2], which are going to play an increasingly important role but which still have a long course of development ahead.

It is useful to examine the temporal evolution in three stages, first with regard to the time horizon primarily discussed in this study, i.e. until about 2030, then until mid-century, and finally, until the second half of this century. The next 10 to 20 years will be needed to develop some key technologies to such an extent that it can then be decided whether they are robust enough in terms of technology and economics to play a significant role in the future. These key technologies include above all CO_2 separation and storage (CCS); success or failure by 2020/30 will be the deciding factor in respect of the possible climate-compatible long-term utilisation of coal. Also to be considered on this time horizon are extending the utilisation of biomass and further development and integration of wind power and solar energy into the grid, including the questions of the potential of concentrating solar thermal power systems in the south of Europe and of real competitiveness of photovoltaics. In the same time perspective, perhaps slightly beyond it, development of the utilisation of geothermal and marine energy could result in energy systems of importance in the European and global contexts. One can also expect international further development of nuclear fission reactor technology (Generation IV) in respect of improved energy yield, security of supply and additional fields of application.

In general, intensified R&D efforts in the various fields are of particular importance in the time period leading up to 2030 and it is obvious that both industry and public authorities need to do more in order to make possible the necessary strategic decisions for or against CCS, in order to select the most economical and

[1] German electricity consumption increaded by 1.2% a year between 2000 and 2008. The particular effect of the financial crisis will probably result in -7.5% in 2009.

[2] The VDI (Verein Deutscher Ingenieure; The Association of German Engineers), for instance, states in its press release on 27 May 2010 that most of the realistic calculations of scenarios, including those of the VDI, predict a share (of electricity) of renewable energy sources between 40 and 50% in 2050.

effective renewable energy systems for avoiding climate change and also, possibly, to reassess the role of nuclear energy in a sustainable integrated energy policy concept. At least to date, the existing German nuclear power plants could support the desired rapid development towards a carbon-free electricity system by their climate-friendly electricity generation (in Germany about 23% of the gross electricity consumption in 2009), should a political decision on extending their life span allow it. The issues mentioned have been discussed in detail in this study.

By 2050 those technologies which have been further developed and are proving their competitiveness could be penetrating the international market to a large extent (preferably supported by – if possible global – carbon emission trading). By then it may be possible for Germany to meet the goal of reducing greenhouse gas emission to, at most, 20% of the figures for 1990; at the same time, it is necessary to succeed in supplementing fluctuating electricity from wind power (and photovoltaics) by flexible, controllable power from biomass, geothermal energy etc. in such a way that security of supply is guaranteed at all times. For this reason, comprehensive extension of the European (high-voltage direct current, HVDC) transmission network is a paramount task.

During the third phase, i.e. in the second half of this century, development must continue to head towards largely carbon-free energy supply. By this time it should have become clear to what extent renewable energy sources can take the lead in the global energy supply and whether nuclear fusion has developed into a clean, technologically and economically competitive energy source (being a carbon- free base load provider, it may thus contribute to guaranteeing high security of supply despite the large contribution of fluctuating renewable energies). It is evident from the analysis of this study that electricity will attain great importance in the long-term energy mix.

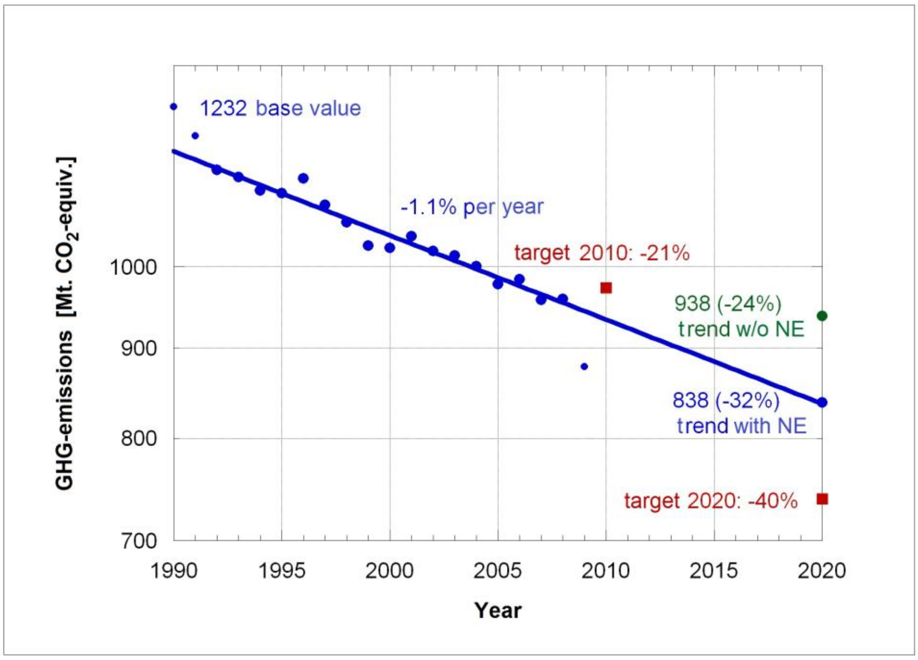


Fig. 1: Extrapolation of the "trend" of greenhouse gas emission (excluding change in land use and forestry) in Mt CO_2 equivalent[3] of the years 1990-2009 until 2020 ("trend" including or excluding[4] nuclear energy) as well as reduction goals for 2010 and 2020. The figure "trend with NE" in 2020 is roughly equivalent to the case of 50% carbon-free electricity generation outlined here.

[3] Source: Data provided by the Bundesministerium für Wirtschaft und Technologie (Germany Federal Ministry of Economics and Technology), Table 10 (as of 8 March 2010, figure for 2009: preliminary estimate)

[4] About 135 TWh from nuclear energy multiplied with the specific CO_2 emissions factor of the fossil-based power plant fleet in 2020 (about 720 g CO_2/kWh, see chapter II.1, Fig. 5) results in savings of nearly 100 Mt CO_2).

There is reason to be optimistic: Utilisation of high-yield offshore areas for generating electricity from wind power is starting up, solar heat is being considered for industrial use, second-generation biomass is expected to open up additional potentials, etc. 50% of Germany's electricity could be generated largely carbon-free by 2020 already if nuclear power plants continue to operate and renewable energies meet the envisaged goal of contributing a quarter of overall electricity generation (see Fig. 1). The 75% margin could be surpassed at a later date; it shall not be discussed here to what extent this might be achieved by fossil-based power plants utilising CCS technology or by further expanding renewable energies or by nuclear power plants or nuclear fusion.

However, if 75% of the overall electricity is generated carbon-free (or, in the case of CCS, carbon-lean) – i.e. each kilowatt-hour generated entails releases of less than 200 g CO_2 on average instead of hitherto 572 g CO_2 in Germany[5] – then it is already more advantageous for climate protection to provide space heating electrically rather than via natural gas: even simple electric resistance heating will then emit less CO_2 than a natural-gas heating system for the same amount of heat. If the efficiency of an electric heating system is improved by a heat pump in a thermodynamically correct way, by a factor of about 3 or 4, then it immediately becomes obvious that electricity is an energy carrier capable of replacing natural gas and even more so heating oil in decentralised space heating.

In this context, the composition of the future electricity mix has to take into account the supra-regional and European distributions. Particularly where there is a high degree of fluctuating wind, solar power or marine energy, interconnection of regions with different weather conditions plays a decisive role in terms of security of supply and cost-effectiveness. This is because trying to achieve sufficient security of supply largely on a national or regional level would require considerable surplus capacities and concurrent high investment and operating costs as well as raise the question of utilisation of surplus electricity. For this reason, electricity generation, distribution and utilisation need to be regarded as a supra-regional (international) system in which generation and consumption always match; this holds as long as possibilities of storing electricity are not available to the desired extent, which, unfortunately, is going to be the case for the foreseeable future. The intended supply-dependent control of electricity consumption via the smart grid may become helpful in this context, but it alone will not be able to solve the problem quantitatively. Overall, the extension of the European transmission network as a "new variable" is of immense importance in optimising the supra-regional balancing of electricity supply and consumption as well as the electricity trade. As soon as a sufficiently powerful European grid exists, current national efforts, such as investments in photovoltaics in Germany, can be much more effectively replaced in the European context by extending capacities at those locations where the natural conditions for that electricity generation are most favourable.

Whether carbon-free electricity will also be able to replace fossil fuels in the transportation sector essentially depends on whether the research into batteries is successful in achieving the decisive breakthrough with regard to the required power densities, charging/discharging cycles and lifetimes at decent prices. Furthermore, it remains to be seen how competition will develop between vehicles powered purely by batteries and those with fuel cells, but also with vehicles utilising advanced combustion engines.

Only global restructuring of the energy system matters with regard to climate change: Carbon-free or carbon-lean technologies need to achieve global dominance and, in order to do so, need to be economically competitive even when taking into account external costs. Accordingly, energy research and development oriented towards global (not only German) possibilities play the key role for Germany as well – both in terms of climate effectiveness and participation in the international market for energy technologies. The share of energy-related activities in the overall R&D efforts has significantly decreased in Germany (and also

---

[5] Source: Umweltbundesamt (UBA; German Federal Environment Agency), Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2008 und erste Schätzung 2009, as of March 2010

worldwide) over the last few decades. Germany has built on direct, immense and decade-long market support for some energy technologies even in the early stages of their development; this is particularly notable in the case of photovoltaics[6]. Improved public subsidisation of energy research and development, in conjunction with calling for a considerable increase in industrial R&D, would be more effective in that it would be considerably more economical and be focused on subsidisation of developmental efforts benefitting the German industry. This way, Germany could profitably play a leading role in the development of carbon-free or carbon-lean energy technologies and of a global, sustainable and climate-compatible energy system.

* * *

[6] In 2009, the commitments concerning reallocation-financed market subsidization for photovoltaic systems installed in Germany in that year alone exceeded public R&D for photovoltaics by about a hundred times and industrial R&D presumably by about seventy times.

Authors and advisers:

(Members of the Working Group on Energy)

Prof. Dr. Walter Blum,
formerly: Max Planck Institute of Physics, Munich
currently: CERN, Genf
walter.blum@cern.ch

Dipl.-Ing. Wolfgang Breyer, Erlangen
former head of
Corporate Communications at
Framatome ANP GmbH
wolfgang.breyer@kerntext.de

Prof. Dr. Hardo Bruhns, Düsseldorf
deputy head of the Working Group on Energy
ake@bruhns.info

Dr. rer. nat. Eike Gelfort, Köln
VDI Nuclear Energy Committee
formerly: BMBF, Ref. 413
e.gelfort@gmx.de

Prof. Dr. Martin Keilhacker,
head of the Working Group on Energy,
coordinator of this study,
formerly Max Planck Institute for Plasma Physics, Garching;
former Director of the JET laboratory, Culham, UK
martin.keilhacker@softdesign.de

Dr. Gerhard Luther,
deputy head of the Working Group on Energy,
former Director of the State Institute of Health and Environment, Saarbrücken,
head of the Office for Future Energy Systems,
University of the Saarland, Saarbrücken
luther.gerhard@vdi.de

Prof. em. Dr. Andreas Otto,
Institute of Experimental Physics of Condensed Matter,
Heinrich Heine University, Düsseldorf
otto@uni-duesseldorf.de

Dr. Matthias Rzepka,
The Bavarian Center for Applied Energy Research
Division: Technology for Energy Systems and Renewable Energy
Rzepka@muc.zae-bayern.de

Dr. Manfred Treber,
Senior Adviser Climate/Transport
Germanwatch e.V., Bonn
treber@germanwatch.org

Dr. Wolfgang Weingarten,
Physicist at CERN, Genf,
European Organisation for Nuclear Research
wolfgang.weingarten@cern.ch

Editors:

Martin Keilhacker
Hardo Bruhns

Imprint:

Deutsche Physikalische Gesellschaft e.V.
(German Physical Society)
Hauptstraße 5
53604 Bad Honnef
Germany
Tel. 02224-9232-0
Fax 02224-9232-50
dpg@dpg-physik.de

Berlin Office:
Magnus-Haus
Am Kupfergraben 7
10117 Berlin
Germany
Tel. 030-201748-0
Fax 030-201748-50
magnus@dpg-physik.de

Press Office:
Bonner Talweg 8
53113 Bonn
Germany
Tel. 0228-5552518
Fax 0228-5552519
presse@dpg-physik.de

This study is available online at:
http://www.studien.dpg-physik.de

Responsible for the content:
Deutsche Physikalische Gesellschaft e.V.
(German Physical Society)

Study

The Deutsche Physikalische Gesellschaft e. V. (German Physical Society, DPG) with a tradition extending back to 1845 is the oldest national physical society in the world, as well as being the largest with more than 60,000 members. The DPG sees itself as the forum and mouthpiece for physics and is a non-profit organisation that does not pursue financial interests. It supports the sharing of ideas and thoughts within the scientific community, fosters physics teaching and would also like to open a window to physics to the public. The DPG brings together professors, students and teachers, those working in industry, journalists and those who are simply interested in physics as such. Former presidents of the DPG include world-famous scientists such as Max Planck and Albert Einstein. The DPG is very particularly committed to equal opportunities for men and women and to promote women in natural sciences.

The DPG itself does not carry out any research, but its conferences offer a platform to discuss the latest findings in the field of physics. The traditional “Spring Meetings” held by the DPG every year at various venues across the country are attended by around 10,000 experts from Germany and abroad. Supporting young researchers is another central concern of the DPG so that its conferences provide a platform particularly for the young generation.

The DPG uses its expertise in the field of physics to engage in socio-political discussions by releasing press statements, carrying out studies, giving statements, organising parliamentary evenings and publishing the fact-sheet “Physik konkret”. Current issues of the DPG are fostering young talent, climate protection, energy supply, arms control and science and cultural history.

The DPG office is located in the “Physikzentrum Bad Honnef” (physics conference centre in Bad Honnef), close to Bonn. The Physikzentrum is not only a meeting place and discussion forum of outstanding scientific significance for physics in Germany but also an international brand for the discipline of physics. Students and cutting edge scientists including Nobel Laureates meet here to share their thoughts and ideas on a scientific level. The DPG is also present in Germany's capital Berlin. It has been running the Magnus-Haus in Berlin since its reunification with the Physical Society of East Germany in 1990.

Deutsche Physikalische Gesellschaft e. V.
Head Office
Hauptstr. 5
53604 Bad Honnef
Tel: +49 (22 24) / 92 32 - 0
Fax: +49 (22 24) / 92 32 - 50
Email: dpg@dpg-physik.de
Internet: www.dpg-physik.de
www.weltderphysik.de