e-HIGHWAY 2050

Modular Development Plan of the Pan-European Transmission System 2050

Contract number	308908	**Instrument**	Collaborative Project
Start date	1st of September 2012	**Duration**	40 months
WP 3	**Technology portfolio to meet the 2050 scenarios**		
D3.1	**Technology assessment from 2030 to 2050**		

Annex to D3.1 - Technology Assessment Report

Supply Block "Generation"

Revision	Organisation	Date
Written by	Dr C. Weise, Dr F. Bauer in close collaboration with the entire VGB Power Tech expert team (Eurelectric)	December 2013
Checked by	E. Peirano (Technofi)	30-06-2014
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Project co-funded by the European Commission within the Seventh Framework Programme

Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	X

e-HIGHWAY2050

Supply Block ´Generation´

VGB PowerTech Report

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December 2013

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Principles

The work has been initiated by EURELECTRIC, in the context of the European project ´e-HIGHWAY2050´, dealing with the interaction between grid and generation. The basis of the work are different investigations and studies listed up in the reference list; e.g. input the demand and supply information into the PRIMES energy model for Europe. The main part stems from the close communication within the VGB PowerTech member community representing the major players in Europe covering the entire range of power generation technologies.

As described, VGB PowerTech has drawn a clear overview of the basic energy conversion technologies transforming primary energy sources into the electricity energy vector also describing all important power generation technologies. The basics of the power generation technologies have been systematically ordered in clear fact sheets as well as with the key characteristics. Information was gathered from the large experience of VGB PowerTech in real projects and operational experience of its members. A qualified projection was made for every technology, stretching the information to 2030 and even 2050.

The conclusions demonstrate the positive role of power generation technologies to curb CO_2 emissions in a cost effective way. Low carbon generation technologies are demonstrated to be the perfect complement to vigorous actions for more efficient use of energy in particular the share of renewables.

Part I - General Overview

1.1 Introduction

The role of power supply within the whole electricity sector is purely service-oriented; i.e. that the demand for electricity has to be supplied in time. In time means immediately because electricity cannot be stored on major amounts. A second decisive attitude of supply of electricity is the necessity of technologies transferring energy contained in primary resources as solar heat, wind blow, fossil fuels or fissile materials and distributing the energy to the consumers.

The key purpose of the supply block is to give an overlook of the major existing technologies based on different primary resources as well as an outlook on the future development. The content of this technology map are the main characteristics and figures for efficiency, emissions and investment costs, fuel costs for today and 2030 and 2050. The actual figures are derived from real projects and placed orders. The descriptions of new technologies are taken from relevant publications on this field, like the International Panel for Climate Change, International Energy Agency (Clean Coal Centre), European Commission, outcome of the Technology Platform ZEP, Zero Emission fossil-fuelled Power Plant, and others, and compiled to one coherent scheme.

1.1.1 Basis of the data

Being aware of the importance of and the public interest for the issues covered in this document, we put all the effort to deliver sound facts reliable in all terms. To do so, we have used and cross-checked as many sources as possible. A particular attention was given to the figures used in the energy scenario respectively of EU, DG TREN, and IEA Energy outlook. The importance of the supply study becomes clear when we take into consideration the evolution of the electricity demand in the upcoming years. There will be an additional demand of power plants up to approximately 300 GW until 2020 due to the ageing of the existing power plant portfolio, the phasing out of nuclear in different countries and the increase of energy demand in the EU-28 member states. An evaluation of the characteristics of the different pathways referring the electricity generation is in this respect extremely important. The portfolio of primary resources is determined by the availability of the technologies needed for and policy measures supporting the necessary investment for new technologies.

1.1.2 Objectives

The block ´Supply´ focuses on the *production* of electricity. It is shown that electricity is indispensable for social development and environment protection. One important observation is that saving primary energy in our daily applications goes along with an increased use of electricity.

Three items will be contained in the block ´Supply´:

- Individual short descriptions of systems, processes and technologies used for the production of electricity out of different primary energy sources;
- Identification of the most important energetic pathways and assessments of their characteristics in 2013, with reassessments in 2030 and 2050;
- Evaluation of the actual system and its anticipated evolution in terms of technology in general and of efficiency, CO_2 emissions and cost of electricity; identification of the efforts necessary to keep the system sustainable and robust.

1.2 Supply – a Balance between primary Resources and Technology

The evolution of the electricity generation sector in the last fifty years up to its actual situation contains a number of lessons that are useful in preparing the future. It is interesting to see how these changes had the – often unspoken – intention to make electricity more available and affordable and to minimize the environmental impact of the activities. It was in some way ´sustainable development *avant la lettre*´; so the plant efficiency was nearly doubled in the last fifty years.

- **A balanced use of primary resources**

The electricity producers always have built their business strategy on a mix of different primary energy resources. It is an important factor in the management of two kinds of risks. The first is the risk of generic problems, which sometimes arise after the introduction of new technologies or materials. The second is the geographic (=political) risk. By using different energy resources, preferably from different regions, this risk can be minimized. The strength of this approach has been shown in a very explicit way at different occasions in the past. Different primary energy resources require different generation technologies, but there are a lot of synergies – one of the most striking examples of the robustness of a balanced use of primary resources.

- **General Remarks ´Technologies and Development´**

Any technical progress is based and limited by laws of nature. These limitations are:

- losses in conversion of resources by applications of physical, chemical or biological effects,
- availability of and access to primary resources,
- energy density of primary resources,
- constraints in distributing the energy in form of electricity to the consumers.

The challenge is to remove or better to tamper all these obstacles in finding a solution and in optimising this solution. Even if there are no limitations in financial and human resources we are not capable and able to trespass the naturally given limits. Generation of power is based on some few principles, which are mechanical energy for rotating turbo machines (steam- and gas-turbines in connection with generators) as well as fluid dynamic systems for hydro and wind machines or physical/chemical effects for direct conversion of primary resources into electricity (Photovoltaic or Fuel Cells and a few others). Other opportunities do not exist; therefore at the end one can give a realistic assessment of the expected technical progress to be made in the next decades – having in mind that the development of new technologies takes time, 20 years at the minimum.

In addition the ´simultaneous issue´ of demand and supply cannot be separated; even new technologies in storage and distribution of electricity would require new technologies. At the end a portfolio of technologies has to be available; available in a sense that there are interdependencies and complementary effects of the different technologies; a prerequisite for a secure supply of electricity. The effects of accessibility, timely availability and energy density of primary resources in relation to the demand side are determining security of supply.

- **Technological innovation and progress**

The electricity generation sector faced essential changes during the last fifty years – with the technology issue as a major factor of influence. New technologies saw the daylight, existing technologies improved and costs were reduced in a very sensible way.

All through these years, we see examples as: the development of gas turbines, technologies for SO_x and NO_x emission abatement, the nuclear technologies, new high-temperature materials, the use of IT technology for better operational efficiencies, the solid state physics as source for the photovoltaic devices and last but not least efficient manufacturing technologies enabling the appropriate production of the components. The essential role played by R&D and technological development in these changes should be underlined once again. The sources and technologies for electricity production are not the same in time and in space. Specific situations lead to specific solutions. The system for electricity generation on an island is different from the one on the mainland. Solar systems are preferably installed in regions with high solar radiation, hydraulic systems where dams can be built or rivers with sufficient current and wind farms where wind is steady and abundant. The impact of access to primary resources and the efficient use of the resources are often expressed as an indicator for a secure supply of energy. In many cases, adapting itself to the specific situation is merely business for the generators.

- **Contributing to the sustainable development**

The electricity generation sector – centralised generation, de-centralised generation, independent power producers and public service providers and others – contributes to a sustainable development by doing its core business. Indeed, raising efficiencies of conversion installations, reducing costs, active search for new sources, are at the heart of the business and, meanwhile, contribute to sustainability. The creation respectively establishing of an open market for electricity is accelerating the process of technical innovation.

1.3 General Survey ´Supply Block´

1.3.1 Domain Covered by the Block ´Supply´

To clearly define which part of the energy scene is covered by the block ´Supply´´, it is referred to figure 1:

At the bottom of the figure (layer 4) there are the energy *products and services*. Just above, in layer 3, under *final energy* the different energy streams are summarized in their *ready-for-end-use* form. Its most universal form is *electricity*; other forms are required for specific services (e.g. liquid fuels for transportation, natural gas for heating).

At the top of the scheme the different *primary energy sources* are presented. These are, in almost all cases, not suited for direct end-use. Between the primary energy sources and their end-use application there is a need for *conversion* (layer 2). Here mechanical, physical, chemical and nuclear processes are used, all these being subject to the fundamental laws of nature (thermodynamic, fluid dynamic etc.).

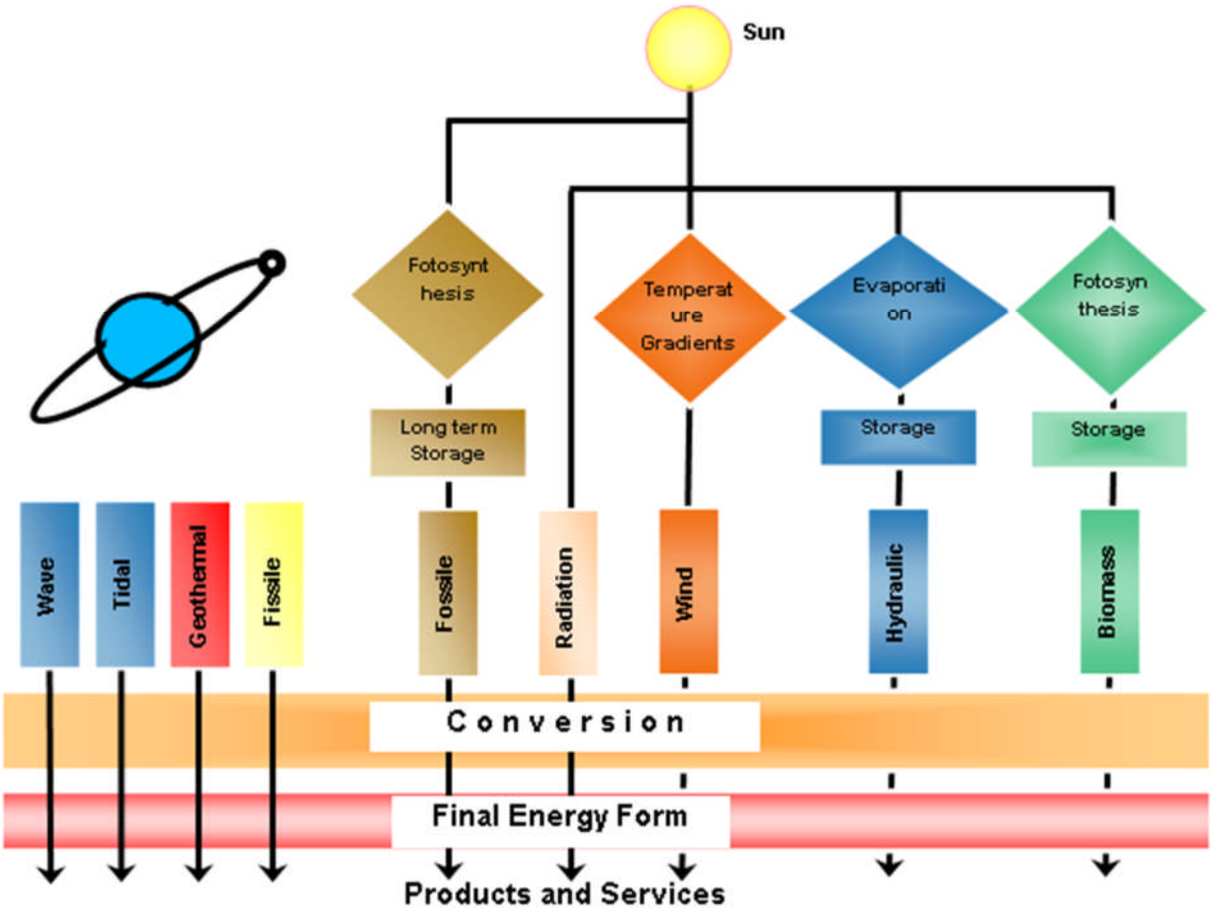


Figure 1: Overview of Energy Sources

The domain covered by the block ´Supply´´ is that part of the *conversion* layer which leads from whatever primary energy source to electricity as energy carrier for the end-use. Consequently appropriate conversion technologies are the key to efficient end-use products and services.

This domain is characterized by a large number of sources and technologies involved. It ranges from very simple processes (conversion of kinetic energy of water or wind into electrical energy) to very complex ones (gasification of coal for use in a combined cycle).

Each way that leads from a specific source via specific processes and technologies to a specific end-use energy form is called an *energetic pathway*.

1.3.2 Principles and Concepts

A closer look at the *conversion* layer is shown in figure 2, in which a simplified description is given of the most common processes which lead from primary energy to electricity. We explicitly have left out technologies needed to realize the processes, in order to avoid the figure to become indigestible.

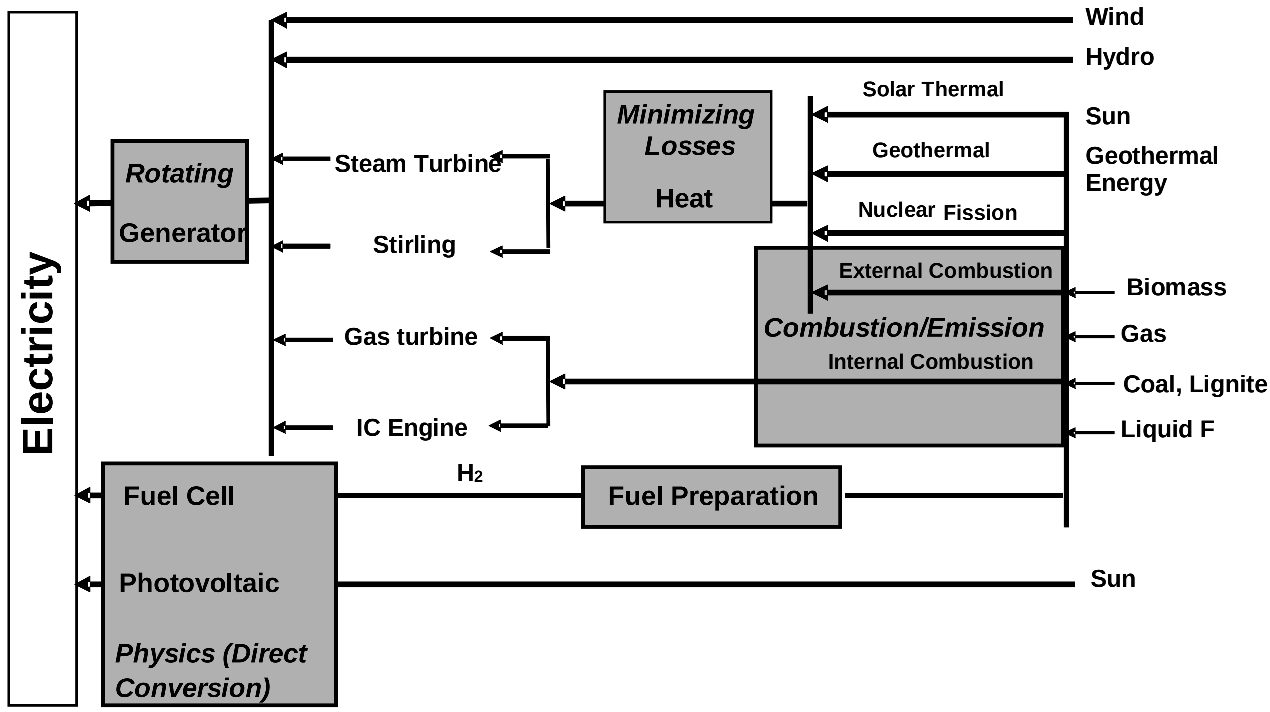


Figure 2: Basic Conversion Scheme

Starting from the left, where the final energy form, electricity, is represented, it is to be seen that three processes lead to that final energy form:

- Transformation of rotational mechanical energy into electricity

This is done in generators. At the right we see how this rotational energy can be generated, either from chemical energy of fuels (combustion, direct or indirect), from nuclear fission, or directly from other forms of mechanical energy (hydraulic or wind energy).

Most of the generators are synchronous (synchronised with the grid), only a few (of small capacities) are asynchronous (can run at different rotational speeds for the sake of raising part-load efficiency potentials). The development of power electronics could have an important impact on this process, as shown in the case of wind turbines.

- Direct conversion of solar radiation into electricity in photovoltaic cells

This is a process of solid-state physics. This conversion process is the most direct one for the use of the solar radiation energy. Unfortunately, the technology is producing direct current power and is quite costly.

- Electrochemical conversion in fuel cells

A much debated application variant is the use of hydrogen in fuel cells. The underlying process is the electrochemical oxidation of hydrogen. Besides, as hydrogen is not a naturally available fuel, it has to be produced from other sources. This topic is analysed further in chapter 1.6.

1.3.3 Evaluation of Energetic Systems

For the evaluation of whether an energetic system (process, machine …) is ´good´´, there is a need for criteria. As interested parties have own concerns and priorities, questions like

´What has the minor impact on environment and climate?´´

´Which primary sources should be used?´´

´Which technologies have the most interesting characteristics?´´

´Where should R&D efforts be directed to?´´

seem to become crucial. To overcome the diversity between the parties we have to look for a common evaluation basis. We are convinced that the concept of sustainable development offers this broadly accepted basis, because it is focused on the customer's interests.

At first, the concept of sustainable development does not offer a set of clear-cut recipes. In fact, there is the need to translate its general principle into more practical rules.

Does the considered energy policy or energy technology...

- contribute to make energy (electricity) more available for everyone? Does it use eventually scarce resources efficiently?
- contribute to make energy (electricity) more affordable for everyone? Does it contribute to reduce the costs?
- contribute to minimise the impact on the environment? Does it avoid irreversible harmful effects?
- ensure to not endanger the possibilities of the future generations?

1.3.4 The Shift in Primary Energy Sources

Although hydro energy and coal still retain their function as important primary energy sources for electricity generation, they were joined during the last 50 years by other sources: Oil, nuclear, natural gas and (new) renewables.

Oil: The heavy fraction of oil from refineries was burnt to some extent in the sixties and seventies in power plant boilers. The so-called pitch was a difficult fuel. Its composition was not stable and its flue gases were corrosive. As the refineries developed technologies to extend the distillation of crude oil, the need of disposal in power plant boilers vanished. Lighter fractions from fuel oil to kerosene have generally been too expensive for electricity generation. Today only very few percents of the electricity come from oil (start-up, back-up fuel).

Nuclear: The use of fissile material (uranium) as a source of energy for the production of electricity started in the mid-fifties and reached industrial maturity by the end-sixties. The installation of nuclear power plants boomed in the seventies, but it nearly came to a stand-still after the Chernobyl accident in 1986. In the EU, about one third of the total electricity production comes from nuclear. It has become the backbone of base load electricity generation. From a global view one can state a kind of nuclear renaissance leading to numerous projects worldwide.

Natural Gas: The use of natural gas for electricity production, which had started as boiler fuel, has experienced a spectacular boom with the development of gas turbines, both industrial and aero-derivative. While some reluctance existed to use this high quality raw material for energy applications, it became a major source of energy for heating, steam boilers, cogeneration and electricity production wherever and whenever fuel prices were competitive.

Renewables: Although renewables had been used since long ago for heating and powering purposes and in specialised applications (e.g. waste wood utilisation in cogeneration mode in the Scandinavian pulp and paper industry), their renaissance came only in the late nineties with the introduction of nationalized subsidy regimes driven by the intention to abate climate change. Small hydro and biomass and wind energy play today important roles in the field of new renewables. It is the general well accepted strategy to intensify the use of renewables as a major step to reduce green house gas emissions.

1.3.5 The Evolution in Existing Technologies

The most important factor in the evolution of the water/ steam-cycle power plant technology was the increase in unit size and its associated ´economy of scale´´. The resulting reduction of fuel consumption and – consequently – of emissions is significant and often underestimated. The evolution was brought about by R&D and technological development in several domains, the most important being fluid dynamics and material science. Especially the continuous efforts to develop high-temperature steels are noteworthy. In parallel, the flue gas was cleaned from pollutants like dust, nitrous oxides and sulphur dioxide.

Figure 3 shows the realized and expected CO_2 reduction potentials through efficiency improvements of coal-fired power plants.

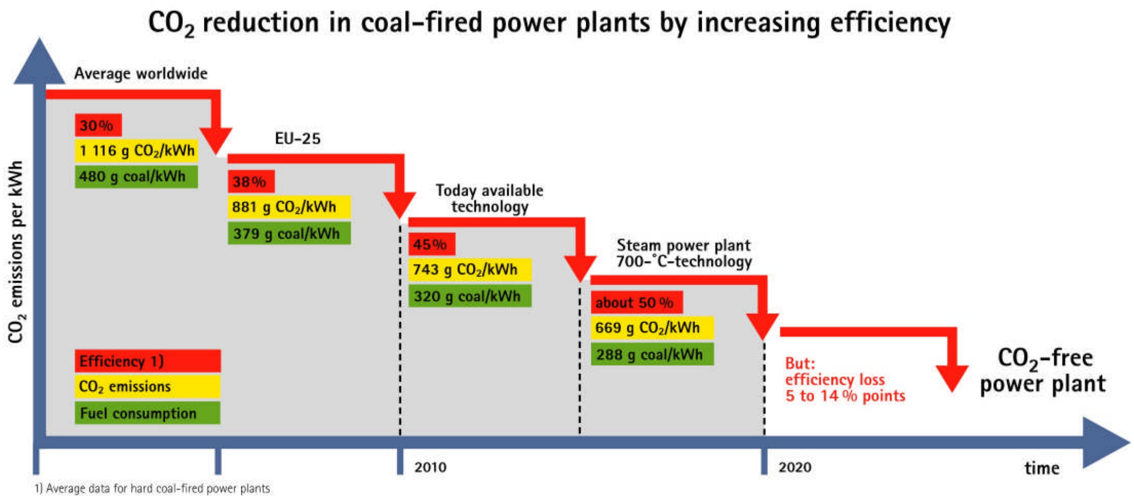


Figure 3: CO_2-Reduction in Coal-fired Power Plants

1.3.6 The Introduction of New Technologies

The introduction of new technologies is governed by the following key factors:

- laws of nature,
- availability of construction material and fuel resources,
- technical maturity,
- competitiveness,
- human resources,
- site requirements,
- impact on environment and climate protection,
- political intentions,
- regulatory framework and
- time and money.

It is beyond the scope of this study to discuss in detail the interactions between the different factors, but the simple listing shows impressively how complex the introduction of new technologies is, examples of which are given below:

Emission abatement: Emission abatement covers the whole range – green house gases and pollutants. Therefore we will deal both the increase in use of renewable resources and the related technologies and the state of the art systems for reasons of environmental compatibility, desulphurisation and de-nitrification systems for flue gases were developed and installed on a large scale. Low-NO_x burners contributed heavily in abating the NO_x emissions.

Nuclear Energy: The use of nuclear is seen differently in the countries of the European Union: clear pro nuclear as well as clear anti nuclear positions. From the beginning, different technologies for the primary part of the power plants were developed in parallel. Finally the pressurised water reactor and the boiling water reactor survived (PWR and BWR). The attempt to introduce breeder reactors on an industrial scale was not successful respectively delayed with new initiatives. The development of nuclear power came practically to a stand-still after the Chernobyl accident. But in the last years new activities have been launched for upgrading the existing technical concepts and for forcing new technical concepts providing more safety and better use of the resources.

Gas Turbines: The use of natural gas is coming more in the focus because the carbon footprint is much smaller as for coal. Remarkable was the success story of the adaption of gas turbine technology for electricity production. Although the gas turbine was known for long, it was the application in aviation that gave its development a first boost. With the introduction of natural gas for electricity production, the land-based (industrial) gas turbine made its way, either for stand-alone (peak power) applications as well as for combined cycles. Unit size and efficiency increased very fast. The development of materials, coatings and blade cooling methods was crucial. Plant efficiency was increased by a factor of nearly two.

Renewables (new): In spite of the fact that the use of renewable sources as hydro, wind and sun is known for more than a century in producing electricity the threat of climate change has launched a tremendous development of technologies. Experience gained from the conventional technologies as material science, design tools, control devices etc. has lead to great success in making the use of renewables more efficient and affordable compliant with the consumers intention. The greater use of renewables has also raised the question for an appropriate system in managing the different technologies according their characteristics. This fact has opened the need for additional non generation related technologies.

1.4 Important Energetic Processes and Technologies

1.4.1 The Complexity of the Conversion Domain

Figure 2 in chapter 1.3 presents very schematically the essential ways that are in use to convert primary energy in electricity. Each of the ways shown consists in fact of a sequence of elementary processes, each of which can be realized by different technologies. All these processes and technologies have their role to play, and it is only the continuous improvement of each of them, and the intelligent interaction between them, that explains the steady improvement in the past. The electricity production sector contributes to the sustainable development by continuously raising efficiency, reducing the emissions and lowering the costs.

Before presenting the most relevant energetic pathways (see Part II) some comments on energetic processes and systems are given.

1.4.2 Combustion

The combustion process is the most widespread chemical process in the world. It consists of the exothermal chemical reaction, i.e. the oxidation of hydrocarbons. The energy of the flue gases can be used directly for process or room heating, or indirectly to produce mechanical energy through thermodynamic cycles.

The fuels can be biomass, waste or fossil fuels; the main components of the fuels are hydrogen and carbon and/or other constituents. The energy of the combustion process can be gained via a heat exchanger in transferring heat of the flue gas into steam and via a combustion piston-type engine in driving the piston by the heat respectively explosion pressure.

The most important characteristics of fuels are:

- the elementary composition,
- the energy content expressed by the higher or lower heating value (excluding or including the vaporisation and heating energy for the humidity or water included in the fuel),
- the theoretical combustion temperature (in the presence of air).

The reaction products can have an important impact on the plant and on the environment. Therefore flue gases are cleaned before leaving the plant through the stack. Solid particles are removed by electrostatic precipitators or bag filters (smaller units). SO_2 is removed by washing the flue gases with a lime solution in a so-called $DeSO_x$ installation. The oxides of nitrogen are reduced through optimized burners (´primary measures´´) or, if not sufficient, with ammonia in a catalytic $DeNO_x$ installation (´secondary measures´´).

The remaining (de-energized) bulk product stream is CO_2. The emission of CO_2, being a greenhouse gas, is now identified as the most relevant root cause and important reason for climate change. The removal of CO_2 will be treated in a separate chapter. Particulate removal, desulphurisation and de-nitrification as described above are end-of-pipe (post-combustion) processes.

An alternative solution to avoid harmful emissions is to treat the fuel before combustion (pre-combustion) in order to remove undesired components and to give the fuel the desired characteristics. This has been done since long in petroleum refineries. In principle this method can also be applied to electricity production, especially for coal and biomass. Biomass and coal gasification with oxygen and steam produces a mixture of mainly CO and H_2, called syngas. This syngas is, after treatment, an excellent and clean fuel. And, after a shift reaction that converts H_2O and CO into CO_2 and H_2, the CO_2 can relatively easily be removed. Pre-combustion technologies provide the intrinsic advantage of much smaller design configurations for the power plant itself than the post-combustion technologies. This is due to the fact that the air/ fuel mass ratio is something like 10. That means that the volume of gas to be treated in post-combustion configuration is about ten times larger than in pre-combustion. This has a significant impact on the volume and the investment costs of the installations.

As long as air is used to provide the combustion oxygen, the associated nitrogen has to pass the power plant as additional mass flow, i.e. a mixture of nitrogen and carbon dioxide. A specific example is the oxyfuel process, in which the combustion of the fuel with pure oxygen is realized consisting of CO_2, water and some pollutants. A combustion with pure oxygen leads to very high combustion temperatures, in an atmosphere of recycled flue gas the combustion temperature can be lowered ready to be used for ´classical´ steam generation. After removal of the pollutants and the water, pure CO_2 remains with a much lower mass flow.

Finally it should be noted that combustion is an irreversible process (although the complete adiabatic combustion without excess air is sometimes called ´ideal´). That means that during the process a part of the exergy is transformed into anergy and is therefore lost for electricity production. Analyses have shown that for nearly all fuels the exergy loss during combustion is about 25percent of the original fuel/ air exergy. That means that the theoretical upper ´Carnot´ limit for the efficiency of thermal conversion processes is about 75percent.

1.4.3 CO_2 Capture, Transport and Storage

CO_2, the most important anthropogenic greenhouse gas – beside methane stemming from ruminant animals, is produced in every process in which carbon is burned. The reduction of CO_2 emissions is therefore seen as the most important way to combat climate change. It is quite easy to understand that the energy conversion sector will have an important role to play in the reduction of the CO_2 emissions. The concentration of important quantities of CO_2 in large-scale fossil-fired electricity production favours these plants for CO_2 capture.

The issue of transport and storage of CO_2 lies beyond the scope of this study and will thus not be treated. Within the framework of the ZEP TP, zero emission fossil fuel power plants Technology Platform, a comprehensive investigation was performed, dealing in detail with the opportunities of carbon storage in geological seams; this paper focuses on the issue of CO_2 capture itself.

For large power plants three possible solutions can be considered, depending on the way the fuel is burned.

- Pre-Combustion

This technology is based on the Integrated Gasification Combined Cycle (IGCC), i.e. coal gasification with gas and steam turbine. Coal is gasified into a synthetic fuel gas through partial oxidation. After cleaning of the fuel gas, the CO of the syngas can be converted into CO_2 by the so called shift reaction that is performed through the injection of steam leaving large quantities of H_2. The CO_2 is then removed from the syngas through a conventional scrubbing process, leaving nearly pure H_2 as fuel. This H_2 can be used for commercial applications (including the production of synthetic fuels), or it can be used directly in a gas turbine of a combined cycle.

- Oxyfuel

The oxyfuel process has two characteristics that make it rather radically different from conventional combustion. The combustion is performed with pure oxygen instead of air and it is performed in an atmosphere of recycled flue gas.

The nitrogen contained in the air is separated from the oxygen in an air separation unit (ASU). The oxygen is used for the combustion, generating a flue gas with a 75 percent smaller mass flow than in conventional combustion. The flue gas downstream of the boiler consists of roughly 70 percent of CO_2, 25 percent of steam and some pollutants. After removal of the water by quenching and removal of the pollutants by scrubbing we get pure CO_2, ready for transport and storage.

- Post-Combustion

CO_2 can be removed from the flue gas of conventional power plants. This is called post-combustion or end-of pipe treatment, the names speaking for themselves. The choice of the capture process depends on the composition of the flue gas (especially the CO_2 partial pressure) and the mass flow of flue gas. For large mass flows with low CO_2 partial pressure, the common removal process is the absorption of CO_2 with alkaline solutions. Common absorption agents are MEA (Mono-Ethanol-Amine), DGA (Ecoamine) and DEA (Di-Ethanol Amine). After the absorption of the CO_2 from the flue gas in a scrubber, the CO_2-rich solution is fed to a desorption tower, where the CO_2 is captured. A new promising absorption agent is ammonium in a chemical looping process.

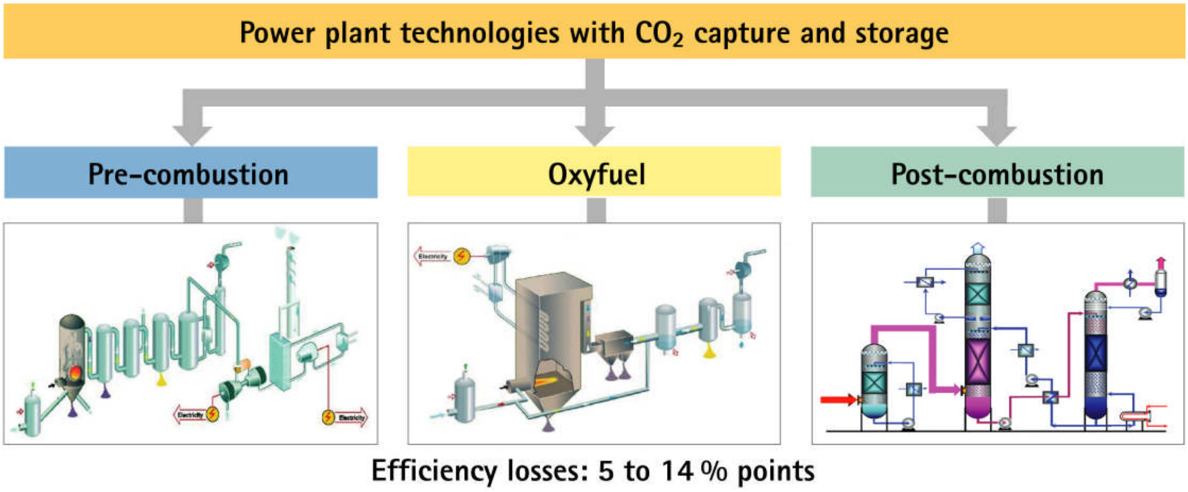


Figure 4: CO_2 Capture and Storage Technologies

In the three capture processes described above, we get CO_2 in gaseous form. Possible options for CO_2 transport are road tankers, railway, ships and pipelines and combinations of them depending on the storage site. For the first three the CO_2 will have to be liquefied. The CO_2 needs to be compressed to a supercritical state (> 73 bar) before transport and storage.

The total amount of mass to be transported will however be huge, nearly threefold to the carbon content of the fuel due to the reaction of each carbon atom with two oxygen atoms.

The compression requires important quantities of power (the compressors are driven by steam turbines or electric motors). It is the consumption of auxiliary power that explains for a large part the reduction of the power plant efficiency by 5 to as much as 14 percent points. The development to optimise the process for achieving minor efficiency losses are in full progress.

1.4.4 Nuclear Fission as an Energetic Process

Today, about a third of the EU electricity is produced from nuclear power, with national shares differing between 0 and 78 percent (France). Although political considerations have slowed down the development of nuclear in some countries, the world now observes a relaunch of interest in the construction of new nuclear power plants, namely in the far east, the US (where all of the 104 existing units have already or will apply for a lifetime extension to 60 years and several new units will be built from 2010 onwards) and in eastern Europe.

In the last 40 years, a steady modernisation process of plant technology and analytical methods took place improving the overall safety level of the plants by a factor of ten over each decade. Today, we look upon an expertise of more than 12.000 reactor operating years (plus the same amount of naval propulsion reactor operating years). No business in the world has shared its operating experience more than the nuclear community.

1.4.4.1 Reactor Technologies – State of the Art & Perspective

Today, there are 441 reactors in operation worldwide; they produce about 17 percent of the global electricity. With the exception of the British gas-cooled reactors, all operating reactors of today were commissioned from 1970 onwards. They form the so-called ´Generation 2´´ and the ´Generation 3´´, the light water reactors are dominant. All existing reactor designs have been continuously improved since then.

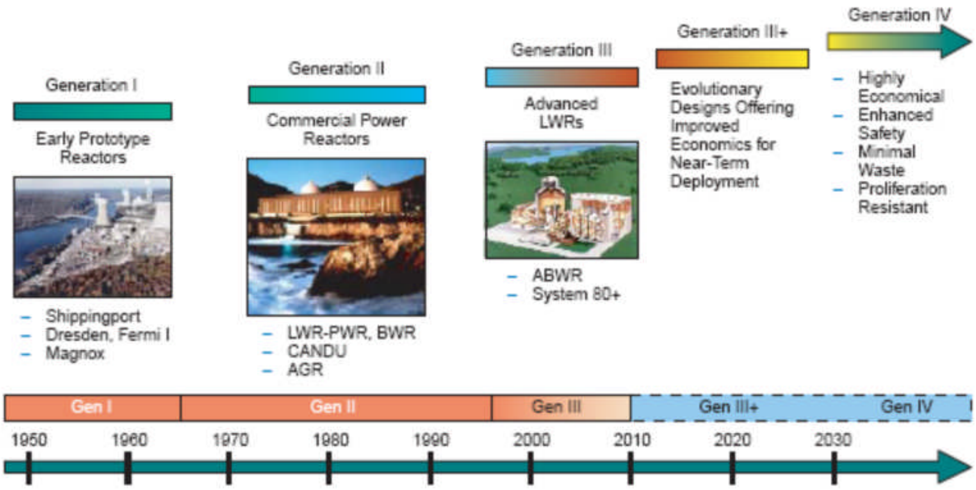


Figure 5: Nuclear Technology Generation

Under construction as ´Generation 3+´´ are also innovative reactor types like the High Temperature Pebble Bed Reactor PBMR in South Africa or the IFBR Fast Breeder Reactor in India.

- Light Water Reactors (PWR and BWR)

Light water cooled and moderated reactors (LWRs) are used nearly in all EU member states. The majority of LWRs in the EU are of the Pressurized Water Reactor type (PWR). On second place is the Boiling Water Reactor (BWR).

Apart from the new construction projects in Finland and France, some EU governments have recently proposed the new build of nuclear power plants or even initiated studies, namely the UK, Poland and the three Baltic States.

Only some of these designs are supposed to become relevant for Europe, European utilities have already short listed design specifications in the so-called ´European Utility Requirements´´. Models ABWR, EPR and SWR-1000 have been examined and validated positively under this scheme by the utilities, the process is going on for AP-1000 and VVER-1000.

- Heavy Water Reactors

The Pressurized Heavy Water Reactor (PHWR) CANDU system is a mature technology. The CANDU designs were originally predicated on optimal thermal neutron utilization to enable the use of natural uranium as a fuel. The Advanced CANDU Reactor ACR-700 is derived from the CANDU-6. Its most obvious modifications are the use of slightly enriched uranium fuel combined with light water as the coolant, allowing a more compact design and a reduced heavy water inventory.

- High Temperature Reactors

HTRs use helium as coolant at a temperature as high as 950°C, permitted by ceramic materials. HTRs have the potential to broaden the utilization of nuclear energy to more cases than power generation, namely

- applications where high temperature heat is required or at least favourable (process industries, desalination, hydrogen production),
- combined heat and power supply,
- cases where modular or decentralized, smaller units (<600 MW_{th}) are requested.

They also open the way to new types of fuel cycles (highly refractory fuel elements ensuring perfect containment for direct disposal or thorium-based fuel)

- Fast Breeder Reactors

Sodium cooled reactors use the fast part of the neutron spectrum, they burn predominantly the U-238 fraction, which is included in natural uranium with 99.3 percent. They thus open up a long- lasting energy resource from even the existing stock of depleted uranium.

1.4.4.2 Generation IV Reactor Technologies, Fusion

Several international think tanks such as the Generation IV International Forum (GIF) launched by the US Department of Energy (DOE) in 2000 and the International Project on Innovative Nuclear Reactor (INPRO) launched by the IAEA in September 2000 identified breakthrough technologies beyond light water reactors (LWRs):

- **Fast neutron systems with a closed fuel cycle** to make an efficient use of natural uranium (80-90 percent as opposed to 0.5 percent in LWRs) and to minimize the long term noxiousness and decay heat of the ultimate waste to be disposed,
- **High or very high temperature nuclear systems** for other energy applications than electricity production such as hydrogen, synthetic transportation fuels, and process heat for the industry.
- **Fusion** is one of the most interesting options which laws of nature offer but difficult to make it real. In an international global cooperation two major projects have to be mentioned: ITER and Wendelstein; the key challenge is en-mantle the plasma at extreme high temperatures enabling the fusion of light elements as hydrogen and helium. The

break through is close to be achieved but for full deployment the horizon is beyond 2040.

The future development paths for nuclear over the existing generation 3 and 3+ designs are based on the above described technology developments. It is expected that nuclear fusion may be able to compete with the advanced fission technologies; its commercial demonstration is, however, not expected before 2050.

1.4.4.3 Fuel Availability and Security of Supply

Even a moderate growth of world-wide nuclear power capacity from today's 370 to 1500 GW_e in 2050 would require over one million tons of natural uranium, if realized only with light water reactors which use less than 1 percent of the uranium (U235 mainly).

For the next decades, the fuel is still abundant. With rising uranium prices, a boom in uranium prospection is currently taking place, extending uranium fuel availability well into the next century for all fuel requirement scenarios.

In general, the fuel price impact on the nuclear cost of electricity will remain at a low percentage, making nuclear investment extensively predictable. Nuclear will therefore also remain to be a *domestic* electricity source, even if the fuel may have come from other parts of the world.

1.4.4.4 Spent Fuel Management and Sustainability

Nuclear waste can safely be disposed off in deep geological formations. The actual nuclear waste (the fission products) which must finally be buried is only about 4 percent of the used fuel, the other 96 percent being re-useable uranium and plutonium.

1.4.4.5 Reprocessing

Closing the fuel cycle requires reprocessing. It reduces fuel demand and the amount of high-level wastes significantly. Light water reactor core layouts can typically include one third of Mixed Oxide (i.e. reprocessed plutonium, blended with U238) fuel. Fast reactors prefer plutonium. In order to minimise the amount of waste isotopes with long half-lives (especially transuranium elements), partitioning and transmutation (i.e. re-irradiation e.g. in reactors to shift to shorter half-lives) of these waste components has been proposed. Costs for this option would be very high, especially for the development and realisation of the reprocessing technologies and the restraints on core layouts, where transmutation would displace power production. From a technical and economical viewpoint, partitioning and transmutation are therefore neither required nor recommendable.

1.4.4.6 Storage of Nuclear Waste

Discussing waste management options, it should be recognized that long decay constantly corresponds to low activity and vice versa.

Due to their very small volume, all kinds of nuclear wastes can safely be stored above ground for long times. However, final storage underground is technically the prime solution. For reasons of public acceptance EU states should and will speed up the development of final underground storages.

Common waste acceptance criteria should be implemented in the EU as well as the legal prerequisites for waste management.

1.4.5 Cogeneration of Heat and Power (CHP)

Cogeneration is an energetic conversion process, in which primary energy is transformed to heat and power, the process being also named commonly CHP (combined heat and power).

The objective of cogeneration is to realize a greater efficiency in comparison to the separate production of heat and power. Whether this objective can be realized and under which conditions will be analyzed below.

But at first one should realize what could be the basic reason for cogeneration being more efficient than separate production. The answer can be found in the application of the two fundamental laws of thermodynamics. The first law is the energy balance (energy input is equal to output for any process); the second refers to the definition of energy as being the sum of (usable) exergy plus anergy (transformation losses). This equation is temperature-dependent and irreversible (heat flows only from higher temperatures to lower).

The production of heat for low-temperature applications (e.g. room heating) by simply burning fuels (high combustion temperature), is unfavourable in terms of exergetic efficiency. The idea of cogeneration is the consecutive utilisation of the whole temperature difference between combustion temperature and ambient temperature in two processes: Use of the large top temperature difference for a power producing cycle and use of the remaining bottom temperature difference for low-temperature heating processes. The variation can range from the extraction of a small fraction of nearly ´devaluated´´ steam (i.e. at a temperature slightly above the condenser temperature) to the parallel utilisation of high temperature heat for power generation in a heating plant. The difference for the operation of electricity grids is significant: The first plants are operated in electricity-production mode (i.e. according to the requirements of the electricity demand), whereas the latter are heat-demand driven.

The four most important technologies used for CHP are: Rankine cycle with steam bleeding, Rankine cycle with back-pressure, gas turbine with heat recovery boiler and internal combustion engine with heat recovery from the flue gases and the motor block.

Whether a CHP in reality realizes primary energy savings and financial profits is a matter of design and operations. It is difficult to give general rules, nearly all cogeneration projects being tailor-made. One thing is sure: Rising fuel prices are favourable for cogeneration.

1.4.6 Electro-Chemical Conversion

The best known example for electro-chemical conversion is the fuel cell. Now, the oxidation can also be performed in a completely different way. The atoms of oxygen can combine with the atoms of hydrogen also in diffusion processes. While the electrolyte is heated up, the migrating ions produce an electrical potential. Using this electro-chemical process, it is possible to come much nearer to reversibility. So, theoretically, the efficiency of the process could be very high. Unfortunately, to realize processes that are near reversibility is difficult. The fuel H_2 has to be conditioned, needing energy for conditioning.

The driving forces are small, so the process goes very slowly and large volumes (or surfaces) are needed. Catalysts can help to speed up the reaction.

So, in principle, there is a process to avoid the exergy losses of the irreversible combustion. The apparatus, in which the electro-chemical oxidation takes place, is named a fuel cell. We shall look in more detail at the fuel cells in the fact sheets.

1.4.7 Solar based Conversion

1.4.7.1 Photovoltaic

Photovoltaic conversion is a solid state physical process, in which the energy of light (´photons´´) is converted in electrical energy using the properties of semi-conductors. The process is the only one that converts sunlight directly into electrical energy. Knowing that the quantity of solar radiation that gets to the earth is many times the human energy consumption, the demand could theoretically be covered completely by photovoltaic conversion. But the technology, needed for the realisation of the process is quite expensive caused by the relative low energy density. The production of the semiconductors, the production of the cells, and the production of the assemblies taken together are responsible for the high investment cost of photovoltaic power plants. Besides (energy density), the intensity of solar energy (in W/m^2) being low, large surfaces are needed to realize the capacities needed. Today, the contribution of the photovoltaic process to the global electricity demand is increasing as the examples Germany and – coming up – Spain and Italy show.

The development of multi-layer PV moduls is enforced enabling efficiency figures of up to 20 percent.

1.4.7.2 Solarthermal

The solarthermal process is a combination of collecting solar radiation and generating steam in an appropriate heat exchanger and turning so a steam turbine. There are different concepts in use respectively in development; these are e.g. parabolic system or central receiver type. The key focus of R&D work is the integration of a heat/steam storage facility. The purpose is to bridge the nighttime and so to extend the overall operating hours. The most favorable approach is the molten salt concept.

1.4.8 Fluid dynamic Systems

Fluid dynamic systems as part of the rotational mechanical energy contain in a stronger sense the hydro and wind power technologies. Steam and gas turbines are also fluid dynamic systems but require a pre-process to bring the machines to turn. The design challenge is to form the rotor blades in a shape enabling optimised use of the resource water or wind; out of this the material design and control systems is the central task for achieving high efficiency and reliable operation conditions.

1.4.8.1 Wind Power Technology

Windmills are a classical technology. Today they are one of the major sources in providing clean electricity. Referring to the technical design features, a power plant consists of the rotor with the blades and the generator. For controlling, the system there is power electronic for steering the blades according to the wind direction and force for optimal harvesting of the wind energy; in supporting this task there can be a gear box installed between the rotor system and the generator. The shape and material choice is the key design challenge. In addition there is a pylon needed as a classical civil engineering work. For off shore wind mills the key element is the foundation on the sea ground and the protection against the corrosive atmosphere.

1.4.8.2 Hydro Power Technology

Hydro power is also an old technology; it is by far the best developed renewable technology. In principal one distinguish between run of river plants and storage based plants. In run of river plants the natural current of rivers or creeks is used. Storage plants store the water by barriers as dams and the electricity can be produced on demand according to the water volume stored in the reservoir (see also Storage chapter). An additional feature is the so called pump storage option where the water can be stored in two basins; after using the water from the upper basin the remaining water in the lower reservoir is pumped up to the upper reservoir.

1.4.9 Storage of Electricity

The storage was and will be in the future one of the key tasks to be solved technically. The main driver is the fact that electricity has to follow – without delay – the demand. In order to balance the different generation technologies in line with the consumers demand there is a necessity to store electricity favourably in an essential amount. The balance requirement stems from the fact that renewables as wind and solar have a variable generation mode according to the meteorological conditions (sunshine and wind blow).

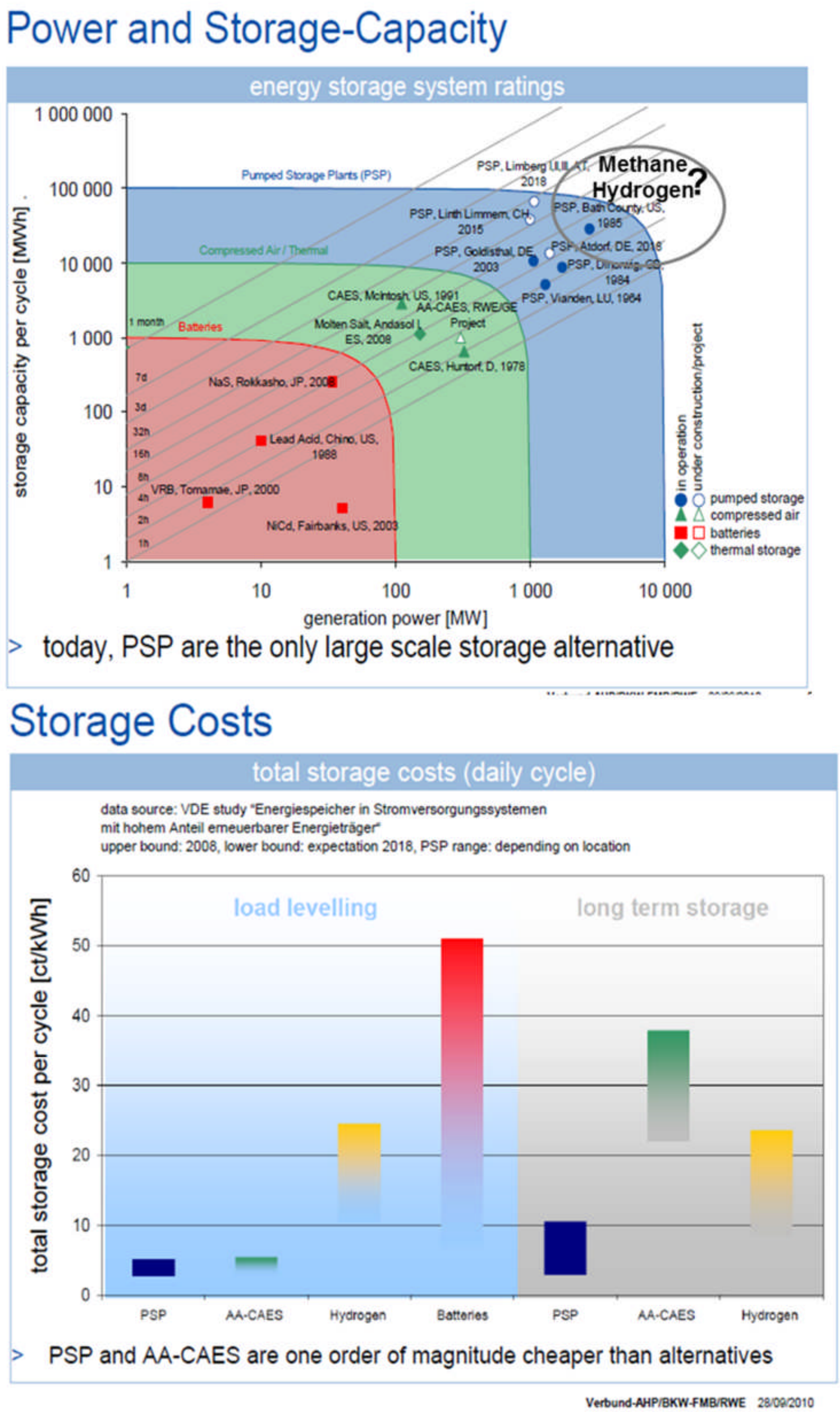
There is a distinction necessary between storage of electricity directly and indirectly via different media and techniques. The main technical solutions for storing electricity are:

- Hydro power (storage/pump storage)
- Compressed air facilities (e.g. CAES)
- Batteries
- Transformation into chemical compounds
- *stored* Heat facilities

The volume which can be stored is limited; it ranges from few minutes in the MWh area (batteries) up to some GWh based on hydro. The potential to increase the total volume of hydro based storage is quite essential in Europe.

The transformation into chemical compounds, e.g. Hydrogen has the potential to offer a larger amount. In this context the power to gas issue can/will play a certain role requiring a new approach referring to the infrastructure.

Another technology is the battery type; forced by the demand for de-carbonisation of the transport sector an intensive R&D activity has been started for developing more efficient batteries applicable for vehicles. The approach is to use the in the vehicles stored electricity to be fed back into the supply system. The expected huge number of electrical vehicles promises a remarkable contribution in balancing; the pre-requisite is the public acceptance to empty the battery in a possible electricity shortage.



Storage and Inertia are the challenges for a stable supply system

Figure 6a/b: Storage capacity and Storage costs for different technologies

The approach to compress air in a cavern and then – if required – to release the pressurised air via a gas turbine in the atmosphere seems simple. But for making this process efficient the storage of the heat generated by the compression process and to recover the heat is the technical issue to be solved. Essential R&D activities have been launched for investigating the potential and for pursuing technical concepts to be tested and demonstrated and deployed; to be mentioned in this context is the CAES technology (A stays for ´adiabatic´ = recovering the heat/cold).

Another approach is to store heat in producing out of the heat electricity via different ways as steam turbines or Stirling motors. In this context the storage of heat by means of molten salt is a technical option to be pursued further on.

In the following figure the technologies and the range of application as well as the expected cost are shown. One can see the technical challenge for making the storage technologies feasible in technical and economic terms.

1.4.10 Learning Curves

The impact of the technical progress is decisive for the future deployment of power generation technologies. Therefore major effort has been spent by VGB PowerTech on the correct and realistic assessment. The methodology developed by VGB based on an extensive analysis; the focus is on the main contributors in a qualitative manner. The rational for applying qualitative figures is the fact that reliable data are only applicable for a time horizon of the next 20 years. For the requested long term perspective the general relation between the different influencing is decisive; in most of the cases quantitative figures cannot be given. An intensive search and analysis of a wide range of publications confirms the approach.

At the end the investment figures will use quantitative date delivering the requested robust data. It is also evident that for investment figures beyond 2030 the degree of uncertainty is drastically increasing. The ever to be respected constraints are the laws of nature.

Consequently the future development of Capex figures depends – beyond other factors – on the technical progress. The manufacturing process or the physical/chemical effects or market impact are determining the technical progress. It is evident that the Capex figures are the pre-requisite for the Opex figures.

Therefore the parameters affecting the cost components of any system able to produce electricity are:

- Physical effects
- Chemical effects
- Simplification of the system
- Process technology
- Material consumption
- Quality of material, e.g. rare earth, platinum
- Engineering ´basic´
- Engineering for specific installation
- Technical maturity
- Standardisation of components and concept
- Manufacturing process → mass production Y/N
- Large scale deployment
- Licensing procedure
- Site impact → geology, meteorology etc.
- Installation and commissioning on site
- Life time impact

The long list demonstrates the complexity influencing the cost structure. In the following it will be shown what one can expect from future developments; in any case we will see at the end a saturation effect. The application of these factors is a relative direct one; step by step the assessment is performed by weighting their relevance (e.g. by crosses). As pointed out in the example the most relevant factors are effects by laws of nature, ´simplification´ of the system, mass production and large deployment and last but not least technical maturity (equivalent with simplification and mass production).

The learning curves, i.e. the improvements in terms of technological progress and cost structure are relevant for the market penetration. As pointed out the different influencing factors have been analyzed.

Three technologies will be considered in its principle features:

Photovoltaic

Referring to the mass production effect Photovoltaic is the most feasible one because the cell production requires a big scale production line; consequently the development cost and engineering cost can be spread on a huge amount of cells. The physical/chemical effect is limited; therefore the process technology is struggling with lower cost per cell but also with lower efficiency and/or shorter life time; consequently a major effect on cost reduction can be expected; aligned by minor efficiency and/or shorter life time. What we see today is the entering of Chinese production into the European market – at very low – too low – prices. According to the laws of market the prices will recover. Some enterprises are struggling with economic difficulties.

Due to the different output and operation condition the cost figures will be normalized at standard efficiency and life time figures to limited gaining's in cost reduction. At the end a level of 1500 €/kW will be realistic. In this context one has to recognize that for the penetration of PV into the market it will not be decisive if the figures are 1200 or 1500 /kW in 30 years from now.

System simplification is focused on the classical part as instrumentation & control system, electric equipment, civil engineering and site specific improvements.

Concentrated Solar thermal Plant

Referring to ´Solar thermal´ one has to distinguish the solar part and the conventional steam turbine part and the storage facility part. At the end the solar part is conventional – except new concepts as Fresnel-type collectors. The cost for the steam turbine part is well known, no surprises will occur. The big unknown is the storage part due to the fact that there is the biggest potential for improvements.

Wind power plants

Referring to wind turbines one has achieved a high degree of technical maturity. Standardised processes are in use. But the mass production effect is reduced on the instrumentation & control system, the electric equipment and the pylon components; the turbine blades itself are requiring a highly sophisticated manufacturing process with very limited mass productivity factor. In addition the site impact is becoming more and more important as the experience shows with the off-shore projects. Off-shore wind is undergoing an intensive learning process; evident is that the potential is limited onto site specific engineering, optimization of civil work as well as design and the reduction of manufacturing/ commissioning cost. All these will lead to a moderate improvement in the costs – ´neglecting´ the dramatic increase of today´s cost.

The connection to decentralised grids with its specific challenges has not been considered.

As a conclusion one can quote that the biggest effect for cost reductions will come from the photovoltaic side. But what we need is a more realistic view as we learned from the off-shore wind power plants, but also from the photovoltaics.

1.5 A Balanced Electricity System

Energy systems are defined by bringing together primary sources, conversion technologies and transport systems to assure the availability of energy (electricity) in a certain country or region.

To secure the robustness of an electricity system, it should be composed of a balanced mix of primary sources and technologies for production and transport. The different elements of the mix and their roles will be shortly described. The main target is the emission reduction of green house gas in the atmosphere.

- Large Capacity Power Plants

Large capacity plants like nuclear, coal fired, hydro or gas fired combined cycle plants provide the base load, i.e. they run continuously.

Besides, large capacity plants assure the stability of the grid system by means of load following (variable load response of a few percent of the unit's capacity). The latter task (´primary and secondary control´ as well as ´ancillary services´) is crucial for an electricity system. As electricity cannot be stored in larger quantities – in spite of huge efforts spent on the development of storage technologies, there has to be a continuous equilibrium between demand and supply. This equilibrium has to be assured for the entire interconnected grid as well as for parts of it (regional equilibrium). This service is offered to the transmission grid operator by large electricity producers. The task is becoming more and more important as more variable or predictable producers are connected to the system.

- Peak Load Units

The demand for electricity is fluctuating over the day and over the year. In some regions the phenomenon of peak demand is very pronounced. Known examples are the regular morning peak or evening peak for cooking. As these peaks have relatively short duration, the use of expensive base load units to cover them is not the most sensible choice. Most electricity producers have dedicated units for peak load covering. These units can be older plants with relatively low characteristics, as well as gas turbines or pumped storage hydro plants.

- Emergency Units

Although the transmission and distribution systems have reached a very high availability, one hundred percent availability cannot be guaranteed. Therefore, sensitive power customers (e.g. hospitals, communications, and nuclear power plants) require extra measures for an uninterruptible power supply. The most used technology is the diesel engines.

- Units based on Renewables

These units take a more and more important place in the electricity production system. There are several reasons for this increase. The more the awareness of climate protection and saving our resources grows, the more people claim for longer term solutions like renewables.

So the use of renewables for electricity production grows, but that has specific consequences, which have to be taken into account. The most important issue is the one of availability and predictability. Whereas the output of conventional power plants is determined by the grid operator. So these renewable power plants cannot essentially contribute to load-following services. This could mean that new transmission lines could be needed to bring the electricity from supply regions to the regions with important demand.

- Cogeneration (CHP) Units

Two applications for cogeneration heat can be distinguished: Process heat production for the industry and room heating. The latter will be treated in the section ´distributed generation´, while we comment here on the characteristics of the so-called industrial cogeneration.

Cogeneration in industry exists since long and has a non-negligible share in the electricity production mix. E.g. refineries and large chemical plants have an important demand for heat as well as for electricity. That means that cogeneration finds here a ´natural´ application. Attention should be given to the operation mode. As industrial cogeneration plants in most cases must be operated in heat load mode, the electrical output is not independently controllable. The supplementary electricity needed to cover the demand is normally supplied from the grid, and its costs depend on the profile. Vice versa, the same can be said about the excess electricity fed into the grid.

- Distributed Generation

The actual electricity system in the EU is based mainly on large electricity production plants. A high-voltage transmission system links the production sites between them. The distribution grids all have a specific ´tree´ structure; the electricity is injected at one point (the trunk of the tree) and distributed to the customers via a branch-like set of cables or lines.

This system has grown historically. The interconnection between the production sites minimises the need for reserve capacity. For all technologies the specific costs (Euro per installed kW) decrease with rising capacity. This leads to the installation of large production plants, with the corresponding need for transmission lines. A new role of the transmission system is driven by the local distance between generation, e.g. wind in the North, and consumer in the South.

In this system, small scale production is limited to specific situations, the most common of which is the *isolated* community (e.g. on a small island). But the share of distributed generation is increasing based on renewables or low carbon emitting technologies, e.g. natural gas.

In particular the difficulties to get licenses for transmission lines, the revival of small-scale cogeneration with internal combustion engines and the prospect on a fuel cell based hydrogen system raises the question of a more general use of distributed generation.

The distributed generation system (also named the embedded generation system) consists of small scale electricity production units, injecting into the distribution grid. Wherever possible, the small scale units are operated in cogeneration mode.

The system claims a lot of advantages: No more need for an expensive transmission system, much lower transport losses, and opportunities for small scale renewables. Most of these arguments are valid up to a certain point. But the distributed generation system has also its natural limits.

The situation changes very radically, when different producers can feed in into the same grid. The tree structure is no longer applicable and all operation procedures, including all safety procedures will have to be changed.

The second issue is the energy management of the system. At all times production has to be equal to demand and that is not evident in a system with cogeneration (where the electricity production is dictated by the heat demand), wind turbines (where the production is dictated by the whims of the wind) and photovoltaic panels (where one can reduce the output by 60 percent). The problem of the energy management brought some people to devise the ´virtual power plant´, in which all the production plants of a distribution grid are managed as ´one plant´.

A third issue is the limited number of primary energy sources available. As coal and nuclear are excluded, the systems can only use renewables (e.g. biomass) and natural gas. As long as the centralised production in nuclear and coal plants, with corresponding transmission lines, remains available as back-up, things are fine. But what if these fall-back solutions are not available anymore? Asking the question is giving the answer. Distributed generation has its specific place with increasing relevance. The major issue is the integration into the system in a technical sense but at the end as a request for a consistent regulatory framework.

1.6 The Hydrogen System

1.6.1 Hydrogen Economy

The need for a sustainable energy supply is becoming more pressing in the light of declining fossil energy resources, environmental pollution, climate change and the increasing dependency on oil imports. In this context, hydrogen is being discussed more and more often as a promising energy source.

Right from the beginning of the discussion about a hydrogen economy it has to be born in mind that hydrogen is not a primary energy source. Instead, it is an energy carrier comparable to the electricity grid or district heating network, and as such it needs to be converted from other sources of energy. Hydrogen is already produced in very large quantities – several tens of millions of tonnes a year worldwide – for use in the process industries.

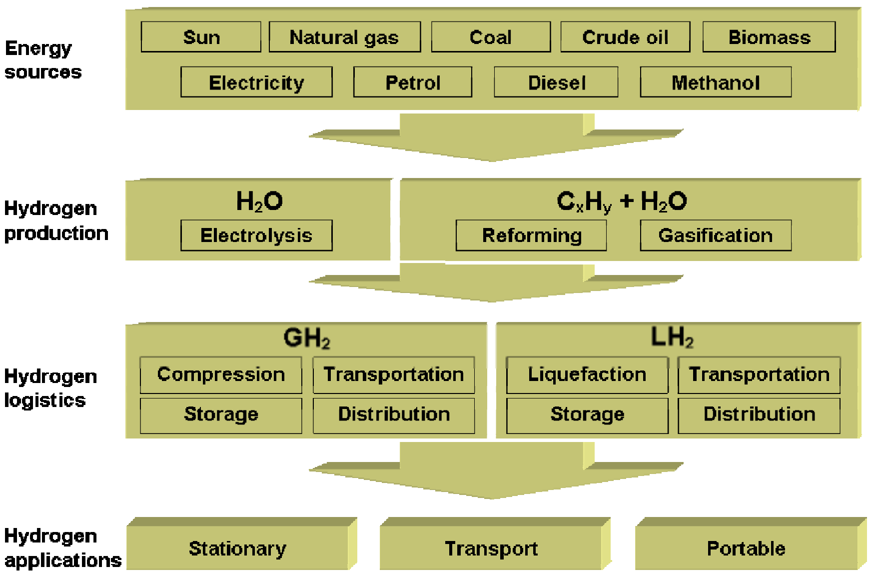


Figure 7: Sub-Systems of Hydro Pathways

If hydrogen is produced in centralised production plants, it needs to be transported to the site of use. Hydrogen can theoretically also be produced decentralised.

1.6.2 Hydrogen Production

Hydrogen is a gaseous, clean energy carrier. It does not occur as a molecule in nature in any significant amounts but can be produced from a wide range of primary energy sources, such as coal, natural gas, nuclear and renewable energy sources. Feedstock preparation or electricity generation is the first step or the first sub-system within a hydrogen pathway.

The main methods of producing hydrogen are:

- electrolysis,
- production from natural gas,
- gasification of coal or biomass (the hydrogen coming from water).

Water electrolysis and natural gas reforming are proven technologies. Electrolysis is an energy-intensive and therefore costly process to produce high-purity hydrogen from water (where the atoms are tightly bound), while the cheaper and more efficient process of gas reforming is used for large scale production where quality is not such an issue. Promising innovative hydrogen production processes are e.g. high-temperature electrolysis or photochemical and biological hydrogen conversion technologies. However, these technologies are still at the very beginning of their development.

- Electrolysis

Electrolysis is a well-known process that splits water into hydrogen and oxygen using electricity. The largest source of electrolytic hydrogen is in fact the chlorine-alkali industry, which has been operating for around 100 years. Electrolysis opens the door to hydrogen production from any renewable and primary energy source that can be used for electricity generation. In this context the power to gas can get a certain role.

The process can be understood as the reverse of a fuel cell where hydrogen is consumed and the electricity is produced. Water electrolysers are commercially available from several companies. The different electrolysers are classified after their type of electrolyte. Today's leading electrolysers are based on a liquid, alkaline electrolyte. Another class of electrolysers are the PEM-Electrolysers (Polymer Electrolyte Membrane). At present, the electricity consumption of the PEM technology is higher than the alkaline based technology; however their long-term energy efficiency potential is better. The PEM electrolysers are close to commercialization, but still too expensive.

The theoretical maximum efficiency of electrolysers is about 85 percent, but current electrolysers are generally less efficient. In the future high-temperature and high-pressure electrolysis may offer efficiency advantages.

- Production from Natural Gas

Hydrogen can currently be produced from natural gas by three different processes:

- Steam reforming of natural gas,
- partial oxidation,
- auto-thermal reforming.

Steam reforming of natural gas is the cheapest way to produce hydrogen. More than 90 percent of the world's hydrogen demand is satisfied using this technology. Natural gas is a mixture of hydrocarbons with low boiling points. It is composed mainly of methane (between 80 and 99 percent) with small amounts of other gaseous hydrocarbons such as ethane and propane. In addition to these hydrocarbons, natural gas also contains nitrogen and carbon dioxide.

Steam reforming involves the endothermic conversion of methane and steam to hydrogen and carbon monoxide. The heat is often supplied from combustion of some of the methane feed-gas. The typical temperatures and pressures are 700 - 850°C and 3 - 25 bar. Depending on the process parameters, natural gas reacts with steam or oxygen to produce a gas composed of H2, CO, CO_2, CH_4 and H_2O. Steam reforming is the most used reforming process on an industrial scale. The overall efficiency of existing plants is in the range between 70 - 80 percent.

Partial oxidation of natural gas is the process where hydrogen is produced through a partial combustion of methane with oxygen gas to carbon monoxide and hydrogen. Auto-thermal reforming is a combination of both steam reforming and partial oxidation. Hydrogen can also be produced from coal and biomass through an endothermic gasification reaction that produces a gas mixture of H_2, CO, CO_2, CH_4 and other components depending on the temperature at which the reaction occurs. A variety of gasification processes (e.g. fixed bed, fluidised bed or entrained flow) can be used.

1.6.3 Hydrogen Logistics

Hydrogen has only a low volumetric energy density. Before it is transported or stored, it is therefore conditioned, i.e. compressed or liquefied. This is particularly important if hydrogen is used in the transport sector, where the tank space is limited. If hydrogen is produced in centralised production plants, it needs to be transported to the site of use.

- Compression

Since hydrogen compression (GH_2) is carried out in the same way as compression of natural gas, the procedure is well tested and readily available. New developments are mainly associated with the optimization of the individual units.

For pipeline delivery, the gas is compressed to 75 bar for 30 bar delivery. For hydrogen cars with a tank volume equivalent to gasoline or diesel cars, hydrogen would need to be stored at a pressure of 700 bar. Compression of hydrogen has significant cost and energy requirements.

- Liquefaction

The special advantage of liquid hydrogen (LH_2) is its high volume-related density, which makes it interesting, in particular, for mobile applications (transport sector). The highest volumetric density is achieved by liquefaction at -253°C. For this purpose, the gas is cooled down in several steps. The liquefaction of hydrogen is potentially a very expensive process. About one third of the energy contained in the hydrogen is needed for liquefaction.

- Hydrogen Storage

Gaseous hydrogen can be stored in conventional steel vessels, or in high-pressure, low weight carbon fibre composite tanks operating at pressures of between 350 and 700 bar. It can also be stored in liquid form at cryogenic temperature of -253°C. Liquid hydrogen storage has been already demonstrated in commercial vehicles.

- Hydrogen Transportation/ Distribution

Once hydrogen is produced, it is then necessary to develop a hydrogen transportation/ distribution system comparable to that now serving electricity, gas or petroleum products. Pipelines have been used to transport gaseous hydrogen for more than 50 years. Several thousands of kilometres of hydrogen pipelines are currently in place. For example Air Liquide operates a network of about 900 km in Belgium, France and the Netherlands. Existing hydrogen pipelines are about 25 - 30 cm in diameter and operate usually at pressures of 10 - 20 bar. It has to be mentioned that the distances between production centres and consumers (mostly big industry) must be small. For a pipeline with the same energy capacity, the cost for a hydrogen pipeline is about six times higher than for natural gas.

Liquid hydrogen can be transported over long distances by ship. The transport of liquefied gases such as LNG is state of the art. However the transport concepts used for LNG are not or only to a limited extent applicable to liquid hydrogen (LH_2) transport due to the low liquefaction temperature.

1.6.4 Hydrogen Conversion Technologies

Hydrogen needs to be converted into power and heat with high efficiency. We have to differentiate between the application in portable small devices, the mobile use in transport and traffic and the stationary application of hydrogen in domestic energy supply or in power plant technology. Hydrogen can be transformed into electricity by different generation technologies, one of it being the fuel cell. Fuel cells are electrochemical devices that combine hydrogen and oxygen in the presence of an electrolyte to generate electricity and heat, emitting water vapour as their primary by-product.

- Transport

Hydrogen can be used to power vehicles by means of internal combustion engines (ICEs) or fuel cells. Since fuel cells have higher useful energy conversion efficiency than simple ICEs, they are very attractive in automotive applications. ICEs, however, are a well established technology. For this reason some car manufacturers are also working on ICEs, especially for hydrogen.

- Stationary

For hydrogen in stationary applications two drivers exist. Electricity can be converted into (storable) chemical energy in the form of hydrogen using electrolysers. One important application for hydrogen in stationary systems is therefore storage of electrical energy in form of hydrogen; for example in uninterrupted power systems (UPS) and for buffering renewable energy sources in remote areas to complement intermittently available renewable sources. These markets are considered as interesting niche markets for hydrogen technology, because high prices are paid for energy (for example for battery/ generator based UPS or diesel generators for a remote site).

- Portable

Portable fuel cell applications can be divided into

- replacement devices for batteries in consumer electronics with power levels of up to approximately 50W (telephones, laptops, etc.), and

- devices for grid-independent power supply in the range up to approximately 5 kW (e.g. camping, emergency power).

1.6.5 Comparative Evaluation of Hydrogen Energy Technologies

A hydrogen economy involves different stages between the production of hydrogen and the end use. The produced hydrogen needs to be packaged by compression or liquefaction to make it marketable. Then this chemical secondary energy carrier has to be transported, stored and distributed. Finally the hydrogen has to be converted into electricity, e.g. in a fuel cell. All these transformation processes lead to a decrease of the total efficiency. Figure 8 shows a simplified analysis of a hydrogen pathway. During the process the amount of the electricity produced is reduced to only approximately <30 percent. Within various international projects different hydrogen pathways for the stationary, mobile and portable energy sector have been analysed. Evaluation criteria were energy efficiency (primary energy demand), carbon emissions and costs.

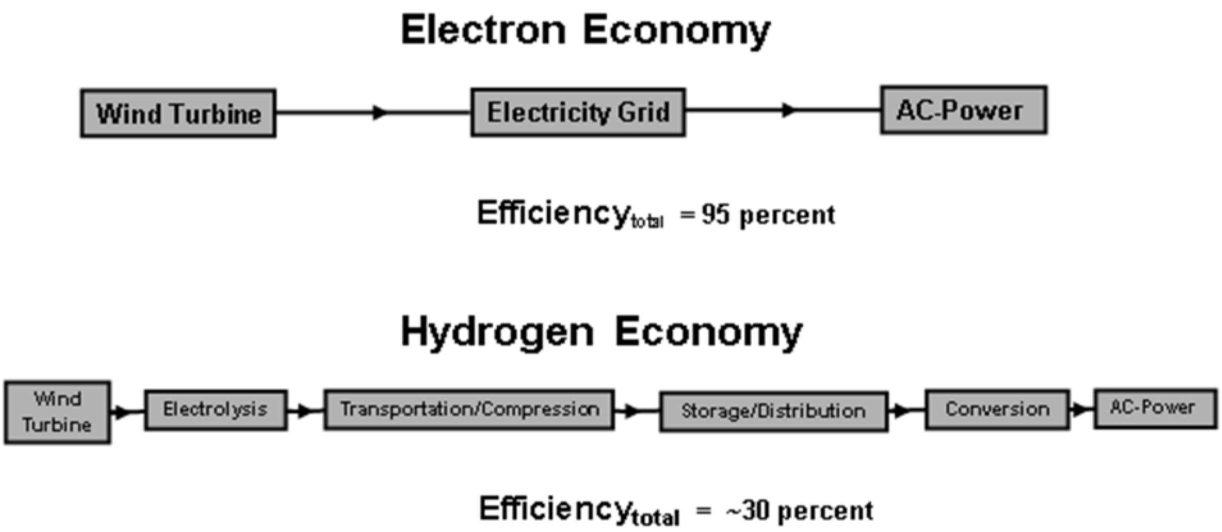


Figure 8: Analysis of a Hydrogen Pathway versus the Direct Use of Electricity

If hydrogen is used as a fuel in the stationary sector, the total costs are continuously higher compared to the direct use of natural gas. This is due to the fact that hydrogen is about 3 to 8 times more expensive than natural gas. For stationary applications (fuel cells, Stirling engines, integrated combustion engines) the generation costs of the hydrogen pathways differ between 10 and 30 Euro-Cent / kWh.

For stationary applications, it can be summarized that the produced electricity should be used directly as long as it is possible to transport the electricity via the transmission grids.

1.6.6 Conclusions and Recommendations

Hydrogen and electricity together represent one of the promising ways to realize sustainable energy, and fuel cells provide the most efficient device for converting hydrogen back into electricity. Although the potential benefits of hydrogen and fuel cells are significant, many challenges – technical, economical and others – have to be overcome before they will be able to offer consumers a competitive alternative.

The first and most important understanding about the proposed hydrogen energy system is that hydrogen is not an energy source. Hydrogen is an energy storage medium and energy carrier. Hydrogen can be produced from a wide range of primary energy sources, such as coal, natural gas, nuclear and renewable energy sources.

Due to the high efficiency losses hydrogen cannot compete with the direct use of electricity. Nevertheless hydrogen can be used in the transport sector in the long term and in special niche applications:

- Hydrogen can substitute gasoline and diesel fuel for road transport and thus eliminate air pollution from vehicles.
- Hydrogen may be used to stretch commercial fuels with methanol.
- Hydrogen may be needed as the basis for synthetic kerosene as aviation fuel.
- Fuel cells for battery replacement and backup power systems are important niche markets in which price and efficiency are relatively unimportant.
- Hydrogen can be used as an energy carrier/ energy storage medium to supply remote areas with energy.

Nevertheless, for both stationary and mobile applications, competing options are also energy measures and large scale electrification based on fossil fuels, nuclear and renewable energy sources. Large scale electrification in conjunction with plug-in hybrid vehicles and Li-ion batteries could also lead to the role of electricity in the transport sector being considered.

Part II - Power Plant Technologies

2.1 Basics of the Fact Sheets for the most relevant energetic pathways

2.1.1 Energetic Pathways

The energetic pathway is a chain, tying a specific primary energy source to a specific end energy form (electricity in our case) via a well defined sequence of conversion technologies.

In part II the most relevant energetic pathways for electricity production are presented in detail. The principles and characteristics of these pathways are laid down in standardised sets of sheets, called fact sheets. The characteristics are destined to summarise the role of the pathway in the sustainable development frame: Environmental compliance, energetic efficiency, emissions and costs.

The energetic pathways have been classified in four families. Governing criterion for the classification is the primary energy source. So we distinguish three families based on their primary energy:

- Fossil fuel based pathways
- Nuclear fission based pathways
- Renewable energy based pathways

A fourth family brings together the pathways that use technologies for small scale generation. Each family is preceded by a short introduction, giving some specific information about the family.

- **Time Frame**

The characteristics of the energetic pathways are given as snapshots at three moments in time:

2010 → 2030 → 2050

The sources for the data are as follows. For 2013, the figures given are drawn from new projects with the best available technology. The figures for 2030 and 2050 are extrapolations from the baseline of 2013. It is supposed that technologies, existing in 2013, will evolve in a steady way. For technologies that are still on the verge of their development phase (new renewables, nuclear fusion), this approach is not applicable. In that case, figures could have been not more than rough guesses.

- **Environmental Compliance**

The environmental compliance is the determining factor ensuring a sustainable future. The compliance is understood as the degree of abatement of the emission of green house gases and the efficient use of our resources – both wind and solar or fossil and nuclear resources.

- **Efficiency**

The efficiency given is the net efficiency. In case of the use of fossil fuels or biomass as primary energy source, the lower heating value is used. This is important when comparing the figures to the ones from USA or Japan, where higher heating values are more commonly used.

- **Emissions**

The key emissions are given by CO_2, SO_2 and NO_x in g/kWh and dust.

2.1.2 Fossil fired power plants

Electricity is produced out of fossil fuels in a chain of processes. First the chemical energy of the fuel is ´liberated´ in a reaction with oxygen, called combustion, producing flue gases. The energy of these flue gases is converted (usually in turbines) into mechanical energy of a rotating shaft. Some variants work directly, others utilize the thermo-dynamical cycle of another fluid. The rotor drives a generator that delivers the electrical energy.

The power plants are characterized by different combustion and boiler technologies. In addition various fuels are used. The fact sheets are presented for the years 2013, 2030 and 2050. CO_2 capture is not foreseen in 2013. For 2030 both cases (with and without CO_2 capture) and for 2050 only the case with CO_2 capture is calculated. The following energetic pathways are presented in the fact sheets:

- Hard coal fired power plants:
  - Plants with conventional pulverised combustion and a water/ steam Rankine cycle
  - Plants with integrated coal gasification and utilisation of the syngas (with shift reactor generating hydrogen) in a combined cycle

  - Plants with conventional pulverised combustion with oxygen and flue gas recirculation and a water/ steam Rankine cycle
- Lignite fired power plants:
  - Plants with conventional pulverised combustion and a water/ steam Rankine cycle
- Natural gas fired power plants:
  - Combined cycle power plants (steam/gas turbine)

2.1.3 Nuclear power plants

The technologies for electricity production from nuclear energy are – for a large part – comparable to the ones used for fossil fuels. It is just in the beginning of the energetic process chain that there is a difference. One use nuclear fission: i.e. the use of heavy atoms (the most common are U235 and Pu239), by irradiation with neutrons the atoms will be split into two lighter fission products with the release of two to three free neutrons. The process also releases energy as radiation respectively heat, the latter of which is transferred to a coolant. A self-sustaining chain reaction can be achieved; if exactly one of these neutrons is able to split another U or Pu atom (the others are absorbed in the other reactor materials or leave the reactor over its outer surface). The rest of the processes in a nuclear power plant can be regarded as conventional transformation of heat into mechanical and afterwards into electrical energy.

Until today, about 500 thermal reactors have been connected with the nets world-wide, most of which still operate (a similar number has been produced for the propulsion of submarines).

In the fact sheets the characteristics of light water, fast breeder and high temperature reactors are treated.

2.1.4 Renewables

The renewable energy sources taken into consideration are hydro power energy, wind energy, biomass, solar radiation and geothermal energy. For the efficient use of renewable energy sources, especially for wind, hydro and solar radiation, the availability of the primary energy is the determining factor. It is striking that the differences in mean wind velocities are high. Wind turbine projects should be realized in those regions where very high wind intensity is present.

It is important to keep in mind that the use of renewable energy sources covers a great variety of primary energy sources and an even greater variety of conversion technologies. So, the fact sheets given should not be considered as covering all for a domain, but rather as representative selection. As an example wind turbines exist in all capacities, each type is having its own characteristics. Also no two sites are identical; the differences in geographical conditions and wind characteristics are important. In the fact sheets only two cases will be described: An on-shore turbine with 2,000 hours full-capacity equivalent and an off-shore turbine with 4,000 hours full-capacity equivalent. Both are realistic cases, but it should be born in mind that these two cases do not represent the whole diversity.

2.2 Basic Data Set – Framework for the Cost Figures

The figures used in the supply block are derived from generators experience in planning, constructing and operating power plants. The figures are embedded in international and European reports like IPCC and IEA Energy Outlook and different investigations and publications. Costs for transport and storage of CO_2 are not taken into account.

2.2.1 Boundaries of Power Plants

Only the conversion installations are considered, as far as they are ´inside the fence´. Office buildings, warehouses and workshops are not included. For coal plants the different storage facilities (coal, ashes, gypsum …) are included. For nuclear power stations the spent fuel storage facilities are included.

For large power plants (coal power plants, nuclear, combined cycles) this study considers one unit at an existing site. This site is already equipped with connections to the transport infrastructure, to cooling water and to the electrical grid, although adaptations may be necessary due to the higher capacity of the new plant. The investment cost includes the EPC, interest during construction and the owner’s costs including licensing procedure.

The boundary on the output side is the generator transformer switchyard. For large power plants, this is the high voltage line that connects the plant to the high voltage grid. For smaller plants, the line can be medium voltage, while for very small plants; the connection to the distribution grid is at low voltage.

2.2.2 Definition of Cost Figures

The principal distinction is given by Capex and Opex meaning the investment cost and operation driven cost. Before entering into the details, some basic remarks are essential.

Referring to the adaptation of the investment costs two issues have to be considered: definition of investment cost and the impact of the market environment and the available resources and last but not least the learning effect for the technologies. In particular the question of resources has played a major role for the coal fired power plant projects under realization until 2016. Lack of experience and new materials have caused extraordinary cost which are not representative in the longer perspective. An even more severe impact could be recognized in the nuclear sector.

VGB has the clear position that such effects cannot be taken into account in face of a 40 years perspective. The market conditions also have – no doubt – an impact too; at the moment for Europe there are no incentives for investments for new power plants – except RES based on specific support schemes – in spite of the fact that back-up capacity is urgently needed. On a global scale there is a huge demand for new generation capacities – coal and nuclear and gas. The prices for investment prices/costs differ essentially; e.g. in China figures are at 60 percent of European one.

In general the definition of investment cost is not clearly elaborated. Therefore we will deal with the different assumptions on investment figures. As mentioned before a precise definition for the investment figures is an absolute must.

The VGB approach is to provide EPC figure only – as decisive part of the Capex cost; owners engineering, cost for financing are not included. This approach follows strictly the approach applied by the OECD/IEA in their publications: e.g. projected Cost of Electricity. The figures listed in table are best estimate figures. The figures are given in 2013 money value; herewith incalculable effects are excluded. The role of erection and commissioning time is considered but not explicitly cited. Costs for tax are treated as variable cost – as part of the Opex cost. Based on a work performed by the Katholieke Universiteit Leuven (Professor D´haesselar) VGB has extended this approach to make evident these influencing factors as shown in table 1.

EPC figure		**1,000 Mio Euro**	**2,000 Mio Euro**
impact	impact figures		
Owners engineering	10 percent	100	200
Financing cost	8 – 15 percent	175 - 250	350 – 500
Construction time	5 years	150	300
Upgrading	10 percent	100	200
Additional cost Mio Euro		**525 - 750**	**1,050 - 1,500**

Table 1: Additional cost for erection

The major conclusion is that – depending on the assumptions and purpose – the figures differ for an amount of nearly two. The purpose is given e.g. by the supply contract, the cost for financing, owners engineering part and finally the investment decision by the investor.

In summarizing the above cited facts the following table provides an overview about basis for the investment figures.

Investment Figures

- Grey field
- Balance of plant – *inside the fence*
- EPC price
- Best estimate figures *with arrange between 8 – 12 percent*
- Figures in 2013 money value
- Time horizon 2013 – 2030 – 2050; *2020 is too close, 2040 no new facts*
- No extra effect taken into account, *e.g. licensing or technical problems*
- Learning impact *according to the described approach*
- Outcome of an inquiry among the VGB members

Finally it is important to make clear that it does not make sense to stress too much cost figures in detail for the next decades, in particular beyond 2030. Having in mind the inevitable uncertainties for scenario investigation relevant is the relation between the different generation technologies; the strict use of 2013 money values together with the prioritized selection of the learning factors mitigates this effect essentially and lowers the overall uncertainty. Much more decisive referring to the implementation of the different generation technologies is the impact of the regulatory interventions and the related cost. In addition, one has to take into account the dramatic changes in the fuel cost mostly influenced by political issues.

The cost of electricity which will be not dealt further is determined by the following contributing factors:

- Investment costs: includes all equipment inside the fence, starting from a grey field, meaning with existing grid and cooling water connections. The investment costs include the engineering and procurement costs (EPC), interests during construction and the owner's costs, including licensing procedure.
- Variable costs: fuel and other materials; CO_2 certificates
- Maintenance and operational costs: Staff, material and contractors
- Costs of support services: Security staff, accounting and personnel services
- Taxes, insurances and other legal obligations: taxes, provisions (e.g. for the management of the nuclear waste, e.g. for the dismantling of the plant).

Very important to determine the specific costs of electricity in EUR/ kWh is the *operational mode*. Parameters that describe this operational mode are time availability and capacity factor. For the latter we use the equivalent ´full-load hours per year´. It should be underlined that the operational mode is not directly a characteristic of the technology. In fact for renewables it depends on the geographical and meteorological situation (sun, wind, water energy) or on the market the plant is working in (for fossil fuel plants and nuclear plants).

Assumptions for the Investment Figures (only for Cost of Electricity relevant)

Furthermore we have to stipulate an interest rate for the investment capital and a depreciation period. Both factors are time- and country dependent. We decided to use the following figures: For the interest rate 10 percent p.a. and for the depreciation period 25 years for gas, 35 years for coal and lignite, respectively 40 years for nuclear power plants (depending on the technology used).

The depreciation time differs between gas, coal, nuclear and wind power plants. The equivalent full power hours per annum have been chosen according to their technical-driven feasibility. The development of technology is taken into account based on realistic learning curves (see part I). The impact of *different* learning curves has been analysed among other sensitivities in the sensitivity cases. The percentage figures for maintenance and dismantling are derived from the generator's experience. The same approach was used for insurance and taxes. They are also expressed as a percentage of investment per year. The mayor factor for the variable costs is the fuel price. The fuel costs, for the purpose of this part of the study, are based on the IEA forecast, adapted for recent price levels.

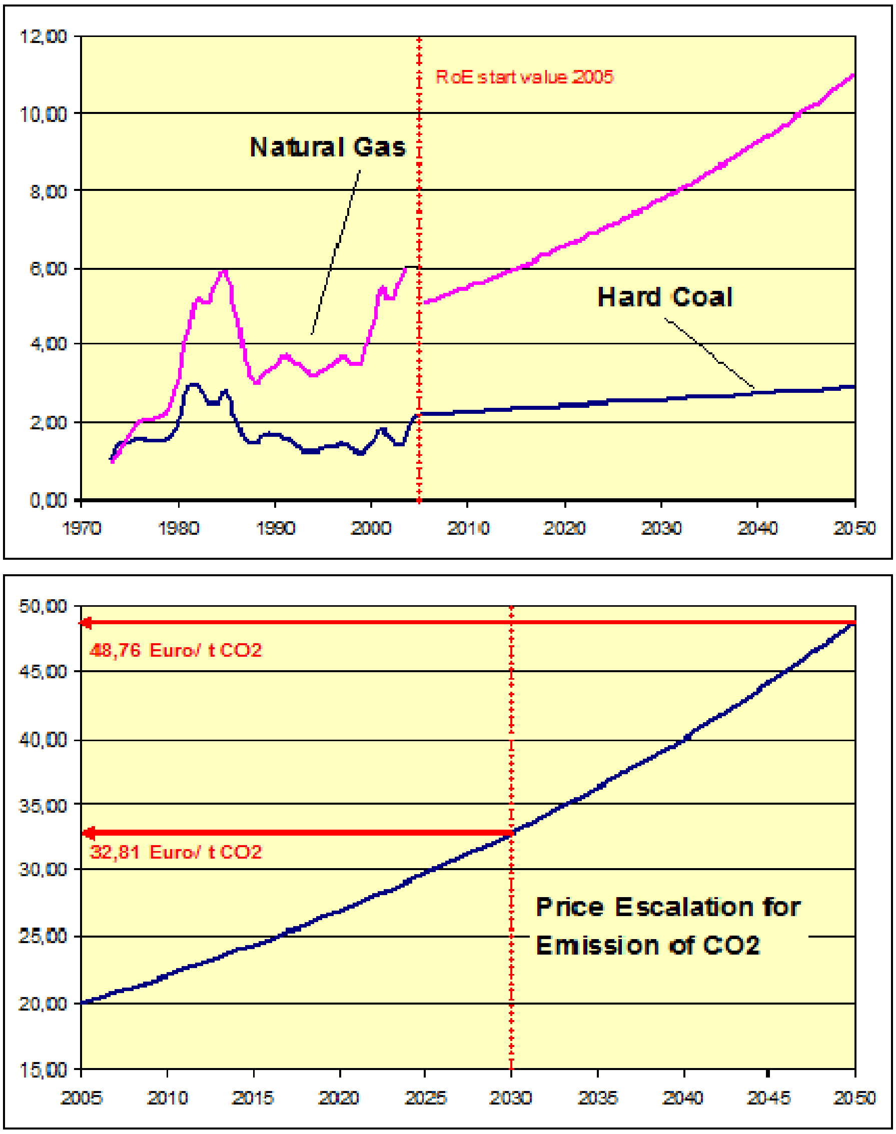


Figure 9 a/b: Price Escalation of Natural Gas and Hard Coal

In the Supply Part of this project, fuel cost calculations are based on a specific hard coal price of 2.47 Euro/GJ and natural gas price of 6.40 Euro/GJ in the year 2013. The considered value for hard coal was selected according to the average values for imported coal in 2013. The basic value for natural gas in the last decade was characterized by high volatility. Therefore, the high average 2013 natural gas price does not represent the right starting point for a long-term consideration. Consequently, it was decided to take as a start-up value the average gas price value of the last 15 years (2000-2013).

The costs for lignite are not quoted on the public market. On the basis of average industrial values 1.44 Euro/GJ were used for 2013.

Concerning the cost for CO_2 certificates the following assumptions are made: The starting value for the CO_2 certificate in 2013 resp. 2020 has been assumed to be 20 €/t. The discussion in the political arena is still going on; the intention is to make the instrument ´Emission Trading´ more effective and in parallel to adapt the subsidy system for renewables.

Once the equivalent full load hours, interest rate and depreciation period are laid down, one has to split up the cost factors into fixed and variable costs. There is a convention to consider the personnel cost as fixed annual costs following the definition used by the European Commission in its Energy Baseline Scenario.

Within the fact sheets the fixed and variable costs are defined as follows:

- Fixed costs:
  - financial costs,
  - personnel costs,
  - maintenance costs,
  - insurances, taxes.
- Variable costs:
  - fuel costs (including the costs of other operating media)
  - CO_2 certificate price.

According to the feedback received during the elaboration the authors are convinced to provide a sound basis for the strategic assessment in the context of future technology development priorities as well as regulatory initiatives or scenario investigations identifying/understanding necessary measures.

2.2.3 Operation Mode – Plant Flexibility and Operating Hours

The last point to be dealt is the impact of the operation mode consisting of plant flexibility and operating hours. The plant flexibility and the annual operating hours are concerning mostly the classical generation technologies, on the cost of electricity. One major effect of the increase of the RES based generation is the reduction of the operating hours of the conventional back-up fleet driven by the fact of the priority dispatch of RES and in parallel the demand for more flexible power plants able to balance the variable RES generation. At the other end there is an absolute need for so-called back-up capacity in order to balance the system as a whole in following the demand and in fulfilling the constraints of laws of nature. If the RES based generation will be integrated into system services – even partially – then the annual operating hours will become relevant for the entire generation fleet.

An inquiry performed by VGB shows in the following table as an overview the key parameter for plant flexibility which are ramp rate up and down, minimum load and time needed to start up (see following table). Intensive development activities are underway for improving these figures; realistic figures for the ramp rate are 10 percent of nominal power in the range of 70 to 100 percent and for the minimum load down to 20 percent of nominal power – mainly for coal fired units, CCGT plants have more limitations due to the power needed for compression of air.

	Nuclear	Hard Coal	Lignite	Combined Cycle	Pump Storage
Start-up Time ´cold´	~ 40h	~ 6h	~ 10h	< 2h	~ 0,1h
Start-up Time ´warm´	< 10h	> 2h	~ 4h	< 1,5h	~ 0,1h
Load Gradient ´nominal Output´	~ 5% / min	~ 2% / min	~ 2% / min	~ 4% / min	> 40% / min
minimal Shutdown Time	← No minimum shutdown time →				~ 10h
minimal possible Load	50%	40%	40%	< 50%	~ 15%

➔ Perspective: load gradient up to 10%
minimum load down to ~ 20%

Table 2: Flexibility in current conventional power generation

For fossil, nuclear, hydro (pump storage and river run) as well as off-shore wind and Photovoltaic the impact of the operating hours will be shown on the levelized Cost of Electricity in additional tables. One conclusion is evident: if according to the limited RES firmness an essential back-up capacity is requested, which is quite accepted, then only via a balanced system approach a sustainable, i.e. secure and affordable, power supply is possible. But in any case there is a high potential for optimization.

The situation today differs essentially from these figures; therefore, the dependence of the levelized cost of electricity of the annual operating hours is shown for the most relevant generation technologies – as an overview. The non-linear function is mainly determined by the Capex cost which can be seen in comparing conventional with RES based generation. Therefore for fossil, nuclear, hydro (pump storage and river run) as well as off-shore wind and Photovoltaic the impacts of the operating hours on the levelized Cost of Electricity are listed up.

One conclusion is evident: if according to the limited RES firmness an essential back-up capacity is requested, which is quite clear, then only via a balanced system approach a sustainable, i.e. secure and affordable, power supply is possible. But in any case there is a high potential for optimization.

2.2.4 Characteristics of the Generation Portfolio

The purpose of the characteristics is to describe the key influencing factors of the most relevant generation technologies. The most influencing factors are:

- Principle of conversion – primary resource
- Technical maturity
- Environmental compliance
- Economics
- Availability of skills and expertise
- Status of suppliers
- Operation mode – flexibility
- System impact – transmission / distribution – centralised and distributed generation
- Perspectives in technical, environmental and economic terms
- Risk Assessment

The assessment is made by allocating chiffres in terms of crosses. The whole description consists of a text part and a table with the different chiffres for the above mentioned factors.

Technology: Hard coal / lignite

Short description of the technology and prospects for its application in the future

- Plants with conventional pulverized coal combustion with air (oxygen) and flue gas re-circulation and a water/ steam Rankine cycle

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- CAPEX
- Carbon prices (including CO_2-emissions)
- System stability
- Environmental compatibility
- Availability of high-sophisticated materials at economic viable prices
- Quality and experience of suppliers

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Loss of experience
- Environmental compatibility (without CCS) – regulatory acceptance and costs (e.g. due to CO_2 emissions)
- CCS breakthrough with respect to technology and public acceptance
- Tendency to decentralized, distributed power generation

Technology: Hard coal / Lignite			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	++
Availability of skilled staff	++	Availability of skilled staff	++
Technical maturity	++	Fuel cost	+++
Standardisation of components and concepts	++	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+	Carbon certificates	+++
Climate conditions	+	Grid fees	++
Infrastructure	++	Feed-in tariffs / taxes	++
Transportation	+	Insurance	+
Licensing	+	Market situation (suppliers)	++
Production technology (e.g. mass production)	+	Quality	+++
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Hard coal and CCGT with CCS

Short description of the technology and prospects for its application in the future:

- CO_2 capture technology is technically available for application in demonstration plants.
- Demonstration plants with CCS technology are under construction e.g. in USA, Canada and Australia, start of operation is planned for 2014/15. In Europe more than 10 demonstration projects are in the planning phase, however no FID (financial investment decision) has yet been taken.
- An increasing amount of renewable power plant capacity has changed the merit order of power plant operation and there is support like FIT (feed-in-tariffs) for RES but not equally for CCS. As CCS will be inevitable to meet the CO_2 reduction targets adequate measures to support the technology deployment are required.
- Lower operating hours of fossil fired power plants in a changed electricity market and the probable need to transport and store the CO_2 offshore at higher costs compared to onshore solutions will extend the introduction phase for application of CCS to coal power plants.
- Based on much higher natural gas prices compared to coal and because of lower CO_2 emissions the application of CCS to CCGT will need even more time to become competitive.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

Fuel cost and carbon certificate prices are decisive factors.

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- The further development of the CO_2 market and the ETS in Europe and even more the global situation is unclear.
- At low CO_2 prices and low operating hours of fossil fired power plants there is no business case for CCS.
- Economic support measures for CCS introduction and a fair level playing field for all energies and technologies are urgently needed.

Technology: Hard coal and CCGT with CCS			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	+
Availability of skilled staff	++	Availability of skilled staff	+
Technical maturity	++	Fuel cost	+++
Standardisation of components and concepts	+	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+	Carbon certificates	+++
Climate conditions	+	Grid fees	+
Infrastructure	+	Feed-in tariffs / taxes	+++
Transportation	+	Insurance	+
Licensing	++	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	+
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Gas combined cycle power plant

Short description of the technology and prospects for its application in the future

The exhaust gas of gas-turbine is the downstream energy of the waste heat recovery boiler. Steam from the boiler is life steam of the steam-turbine. In connection with power to gas and gas to power CCPP will be the main column on the energy market.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availa-bility)

Less experienced manpower in the future.

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- No particular risk
- Load factor might be not enough to payback investments
- Technology in competition with on-demand storage facilities
- Depends a lot on capacity market and on payment of ramping capability

Technology: Combined cycle power plant			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	+
Availability of skilled staff	++	Availability of skilled staff	++
Technical maturity	++	Fuel cost	+
Standardisation of components and concepts	+	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+	Carbon certificates	+
Climate conditions	++	Grid fees	+
Infrastructure	+	Feed-in tariffs / taxes	+
Transportation	+	Insurance	+
Licensing	+	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	+
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	++

+++ – high, ++ – middle, + – minor, - – no

Technology: Open cycle power plant

Short description of the technology and prospects for its application in the future

The exhaust gas of the gas-turbine goes directly into the air.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

Less experienced manpower in the future.

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

No risk. It will be a marginal technology due to the poor efficiency.

Technology: Open cycle power plant			
Influencing Fac-tors	**Influence on the CAPEX**	**Influencing Fac-tors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	+
Availability of skilled staff	++	Availability of skilled staff	+
Technical maturity	+	Fuel cost	+
Standardisation of components and concepts	+	Efficiency	+
Material	+	Operating hours	+
Geographical condi-tions	+	Carbon certificates	+
Climate conditions	+	Grid fees	+
Infrastructure	+	Feed-in tariffs / tax-es	+
Transportation	+	Insurance	+
Licensing	+	Market situation (suppliers)	+
Production technol-ogy (e.g. mass pro-duction)	+	Quality	+
Market situation (suppliers)	+	Spare parts or any other retrofit hard-ware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Small and Modular Reactors < 400 MW

Short description of the technology and prospects for its application in the future

- In the recent years, some new plant designs have been proposed to the market: large scale plants of more than 1,000 MW capacity, such as EPR and AP 1000, but also a new category of small-modular reactors (SMR) with an electrical output lower than 300 MW and a modular conception.
- Historically, all early reactors were smaller in size compared to those deployed today and the general trend has always been toward larger unit sizes, which allows for lower specific investment and O&M costs due to the economy of scale.
- Large nuclear power plants (above 700 MW) constituted more than 80 percent of the nuclear capacity connected to the grid after 1990, while small reactors represented only 4 percent of the total capacity installed.
- Currently, the deployment of SMRs has been envisaged in niche markets that cannot accommodate large nuclear power plants: this applies to remote or isolated areas where large generating capacities are not needed, electrical grids are poorly developed or absent, and where non electrical products (such as heat or desalinated water) are as important as the electricity. In those markets, SMRs are competitive with coal-fired, gas-fired or renewable plants.
- Beside those niche markets, deployment of SMRs is also considered in traditional markets, in direct competition with large NPPs.
- With respect to large reactors, SMRs benefits from design enhancements and simplifications allowed by the smaller scale (i.e. enhanced passive safety, fewer components, better plant layout, etc.). In particular, their smaller size eases their siting and integration into the electrical grid and guarantees a stronger operational flexibility.
- From an economic viewpoint, SMRs have a higher specific investment cost and consequently higher levelised cost of electricity production (LCOE) than larger nuclear units.
- However, SMR are characterized by shorter construction time, by a much smaller up-front capital investment and by the possibility to increase progressively the nuclear capacity and to react quicker to changing market conditions. Those characteristics results in smaller financial risk, making such reactors potentially attractive to private investors and to countries initiating a nuclear program.

- Most SMR designs provide long operation periods between refuelings (up to ten years). This, together with turnkey delivery of workshop production, will enable new, simplified operation, maintenance and staffing modes.

Factors that influence the costs today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Licensing and regulatory infrastructure required
- Abundant fuel resources available same as for large nuclear
- Small Medium Reactors could be an important component of the worldwide nuclear renaissance because they require a limited front-end investment effort, usually have characteristics of simplicity, enhanced safety and offer an option to increase the power generation capacity by adding successive NPP modules on the same site. This makes SMR a ´modular´ investment concept, characterized by the option of small power increments through the deployment of successive NPP units. SMRs thus offer the investors higher flexibility than large reactors in the investment decision.

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- SMRs have a significant potential for expanding the peaceful applications of nuclear power by catering to the energy needs of those market segments that cannot be served by conventional NPPs with large reactors. Such segments could be:
    - Niche applications in remote or isolated areas where large generating capacities are not needed, the electrical grids are poorly developed or absent, and where the non-electrical products (such as heat or desalinated water) are as important as the electricity;
    - Replacement for decommissioned small and medium sized fossil fuel plants, as well as an alternative to new-plants, in cases when certain site restrictions exist, such as limited free capacity of the grid, limited spinning reserve, and/or limited supply of water for cooling towers of a power plant. Also, replacement of fossil-fuelled combined heat and power plants (the SMR power range seems to better fit the requirements of the currently existing infrastructure);
    - Power plants in liberalized energy markets or those owned by private investors or utilities for whom small upfront capital investments, short on-site construction time (with the accordingly reduced cost of financ-

ing), and flexibility in plant configuration and applications matter more than the levelized unit electricity cost.

- No situations have been found where NPPs with SMRs could compete with state-of-the-art large reactors. However, the SMRs could be competitive with many non-nuclear technologies in cases when NPP with large plants are, for whatever reason, unable to compete.
- The challenges for the SMRs are licensing, siting, multiple units/modules on the same site, the number of reactors required to meet energy needs (and to be competitive), and the general public acceptability of new nuclear development

Technology: Nuclear Power < 400 MW			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+ (negligible)	Staff/Labor costs	++
Availability of skilled staff	+++	Availability of skilled staff	+++
Technical maturity	++	Fuel cost	+
Standardisation of components and concepts	+++	Efficiency	+
Material	-	Operating hours	+++
Geographical conditions	++	Carbon certificates	-
Climate conditions	-	Grid fees	+
Infrastructure	+	Feed-in tariffs / taxes	+
Transportation	+	Insurance	++
Licensing	+++	Market situation (suppliers)	+
Production technology (e.g. mass production)	++	Quality	++
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Nuclear Power > 700 MW

Short description of the technology and prospects for its application in the future

- In the next decades, about 500 light water reactors in more than 30 countries will provide between 10 and 15 percent of the worldwide power generation.
- Very low life cycle production costs of average 1 to 2 Euro ct / kWh if allowed to run for e.g. 60 years.
- Ideal for base load generation due to very low OPEX (about 30 percent; insurance, decommissioning and storage included); of these, very low fuel costs (about 5 percent).
- Also well capable of load follow requirements due to high power gradients (5 percent / min, equal to e.g. 70 MW/min, 10 percent / min theoretically possible), already built into the designs.
- In some cases high prototype CAPEX costs for new designs, can be reduced to 2000 €/kW for series production.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Licensing and regulatory infrastructure required.
- Having depreciation periods of 15 to 20 years, paramount importance lies on life time (60 years or more technically feasible).
- Existing GEN-II reactors had/have to be refurbished to GEN-III standard (incl. new digital I&C after half life period).

Abundant fuel resources available:

1) Conventional uranium for several hundred years.

2) Thorium (4x more abundant in the earth crust) possible, but still to be developed.

3) Uranium extraction from sea water (thousands of years) used to be tenfold more expensive, with new technologies near competitiveness.

4) Utilisation of large stocks (thousands of years) of depleted U-238 in closed fuel cycles (reprocessing plus GEN-IV fast breeders).

Final storage technically no problem.

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

1) Political acceptance (in few countries).
2) Raising of capital.

Worldwide power generation will increase to 200 to 300 percent. Economic optimum would be to cover its base load fraction of e.g. 80 percent by hydro (30 percent) and nuclear (50 percent). Thus decarbonisation of worldwide power systems economically feasible, including large-scale production of synfuels and seawater desalination.

Nuclear energy is the sole carbon free energy that can be generated in a stable and dispatchable manner. Except for some reluctant countries, most countries embarking nuclear in EU will renew their nuclear fleet with more flexible capability.

Technology: Nuclear Power > 700 MW			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+ (negligible)	Staff/Labor costs	+
Availability of skilled staff	+++	Availability of skilled staff	+++
Technical maturity	+++	Fuel cost	+
Standardisation of components and concepts	+++	Efficiency	+
Material	-	Operating hours	+++
Geographical conditions	-	Carbon certificates	-
Climate conditions	-	Grid fees	-
Infrastructure	++	Feed-in tariffs / taxes	-
Transportation	-	Insurance	+ (negligible)
Licensing	+++	Market situation (suppliers)	+
Production technology (e.g. mass production)	++	Quality	++
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Hydropower

Short description of the technology and prospects for its application in the future

- Hydropower is the one of the most important RES applications in Europe.
- The furthermore exploitable potential differs in the EU member states; it is however, indicated in the EURELECTRIC-Report ´Hydro in Europe Powering Renewables´.
- Besides Hydropower, i.e. Reservoir or Pumped Storage, can provide necessary intermediate storage capacities for surplus electrical energy in the transmission grid on large scale to guarantee a secured energy supply on the basis of other RES applications (wind, solar).

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Hydropower is a nature technology with high efficiency rates.
- Further technical development is possible especially to increase flexibility expectations.
- Decisive changes of investment or maintenance costs are not recognizable.
- Imponderables with regard to cost increases exist concerning possible new taxes or environmental compensation measures.

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Severe restrictions might arise from different environmental ordinances, e.g. the EU Water Framework Directive.
- Considerable expenditure for the new execution or retrofit of environmental compensation measures (fish ladders for migrating fish, biotopes, leisure parks etc.) as well as electricity production losses due to modified operational circumstances (raised residual water amounts in diversion stretches etc.) decisively increase investments and decrease revenues.

Technology: Hydropower			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	+
Availability of skilled staff	+	Availability of skilled staff	+
Technical maturity	+	Fuel cost	+
Standardisation of components and concepts	+	Efficiency	+
Material	+	Operating hours	+
Geographical conditions	+++	Carbon certificates	+
Climate conditions	+	Grid fees	+++
Infrastructure	++	Feed-in tariffs / taxes	++
Transportation	+	Insurance	+
Licensing	++	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	+
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Wind on-/offshore

Short description of the technology and prospects for its application in the future

- Wind turbines are built to transform the kinetic energy of the wind into electricity.
- The most common type today is a three-blade, horizontal axis, pitch controlled wind turbine with synchronous generator and ac-dc-ac power conversion.
- The main components of a wind turbine are foundation, tower, rotor blades and the energy conversion system (e.g. gear box, generator).

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manu-facturing today and 2050, mass production, material availability, resource availability)

- High operation and maintenance costs
- Development of longer blades
- Development of lighter rotors
- Increase of capacity
- High foundation and grid connection costs (offshore)
- Uncertainty of grid connection (offshore)

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Lack of grid extension
- Safe disposal of blades
- Licensing

Technology: Wind on-/offshore			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	++	Staff/Labor costs	++
Availability of skilled staff	++	Availability of skilled staff	++
Technical maturity	+	Fuel cost	-
Standardisation of components and concepts	+	Efficiency	+
Material	-	Operating hours	+++
Geographical conditions	+++	Carbon certificates	+
Climate conditions	++	Grid fees	+
Infrastructure	++	Feed-in tariffs / taxes	+++
Transportation	++	Insurance	+
Licensing	++	Market situation (suppliers)	+
Production technology (e.g. mass production)	++	Quality	++
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	+++

+++ – high, ++ – middle, + – minor, - – no

Technology: Biomass standalone

Short description of the technology and prospects for its application in the future

- 100 percent biomass combustion
- Most suitable combustion technology: grate fired boilers and fluidized bed boilers
- Biomass plants can run in base load and compensate the fluctuating production of other renewables as long as the fuel is available
- The cost of the electricity depends on the biomass feedstock price
- The operation of the biomass power plants depends on the characteristics of the biomass feedstock
- Higher operation costs in comparison to fossil fired power plants
- Biomass plants should be used in cogeneration mode for heat and power, whenever possible

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Incentive system
- Biomass availability, quality and price
- Establishment of supply chains
- Limitation of corrosion on furnace walls and superheaters
- Storage of biomass fuel
- Ash disposal/utilization

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Securing sustainable Biomass production and supply chain
- Public acceptance and opinion
- At large scale DeNOx catalyst poisoning

Technology: Biomass standalone			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	++
Availability of skilled staff	++	Availability of skilled staff	+
Technical maturity	+	Fuel cost	+++
Standardisation of components and concepts	++	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+	Carbon certificates	+
Climate conditions	+	Grid fees	+
Infrastructure	++	Feed-in tariffs / taxes	+++
Transportation	++	Insurance	+
Licensing	+	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	++
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Biomass co-firing

Short description of the technology and prospects for its application in the future

- Combined combustion of biomass and fossil fuel; also conversion of coal fired power plants.
- Biomass co-firing plants can run in base load and compensate the fluctuating production of other renewables as long as the fuel is available.
- The cost of the electricity depends on the biomass feedstock price.
- The operation of the co-firing power plants depends on the characteristics of the biomass feedstock and the co-firing share.
- Higher operation costs in comparison to coal fired power plants.
- Co-firing of biomass in coal-fired boilers without changes to boiler and equipment is limited to about 10 percent of the conventional capacity.
- For higher shares of co-firing boiler and equipment have to be modified.
- The additional investments for co-firing of biomass in coal fired power plants are low in comparison to stand alone plants.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Incentive system
- Biomass availability, quality and price
- Establishment of supply chains
- Limitation of corrosion on furnace walls and superheaters
- Storage of biomass fuel
- Ash disposal/utilization
- Suitable milling equipment (pulverized fuel boilers)

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Securing sustainable Biomass production and supply chain
- Public opinion / acceptance
- At large scale DeNOx catalyst poisoning

Technology: Biomass co-firing			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	++
Availability of skilled staff	+	Availability of skilled staff	+
Technical maturity	+	Fuel cost	+++
Standardisation of components and concepts	+	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+	Carbon certificates	++
Climate conditions	+	Grid fees	+
Infrastructure	++	Feed-in tariffs / taxes	+++
Transportation	+++	Insurance	+
Licensing	+	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	++
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	++

+++ – high, ++ – middle, + – minor, - – no

Technology: Photovoltaic

Short description of the technology and prospects for its application in the future

- Photovoltaic (PV) cells, or solar cells, convert sunlight directly into electricity.
- PV cells are assembled into panel systems.
- A photovoltaic module is composed of interconnected cells that are encapsulated between a glass cover and a weatherproof backing.
- The electricity generated by a PV module is in the form of direct current (D.C.).
- Transformation of direct current to alternating current (A.C.) required by many common appliances and for grid connection is achieved with an inverter.
- They generate electricity with no moving parts, operate quietly, and require little maintenance.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Incentive system
- System stability
- Environmental compatibility
- Safe disposal of hazardous chemical waste
- Mass production

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- System stability
- Reliable power supply
- Life time

Technology: Photovoltaic			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	+
Availability of skilled staff	+	Availability of skilled staff	+
Technical maturity	+	Fuel cost	-
Standardisation of components and concepts	+	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+++	Carbon certificates	+
Climate conditions	+++	Grid fees	++
Infrastructure	++	Feed-in tariffs / taxes	+++
Transportation	++	Insurance	++
Licensing	+	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	++
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Concentrated Solar Power

Short description of the technology and prospects for its application in the future

- Solar thermal power plants use the high-temperature heat from Concentrating Solar Collectors (CSP).
- The heat can be used directly or can be converted into electricity. The main components of a CSP System are

  - the solar collector field,

  - the solar receiver (mounted on the collector),

  - the energy conversion system.

- Parabolic trough systems are the most developed and tested technology for solar electricity generation on a power plant scale

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Increased fluid outlet temperature
- Increased efficiency of the solar and conventional power block
- Cost reduction through mass fabrication
- Improved system availability and reduced operation and maintenance costs
- Development of efficient and cost effective storage systems
- Development of hybrid systems

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Increased use of PV instead of CSP
- Insufficient cost reduction

Technology: Concentrated Solar Power			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	++	Staff/Labor costs	++
Availability of skilled staff	+	Availability of skilled staff	++
Technical maturity	+	Fuel cost	+
Standardisation of components and concepts	+	Efficiency	++
Material	++	Operating hours	+++
Geographical conditions	+++	Carbon certificates	+
Climate conditions	+++	Grid fees	++
Infrastructure	++	Feed-in tariffs / taxes	+++
Transportation	++	Insurance	+
Licensing	+	Market situation (suppliers)	+
Production technology (e.g. mass production)	++	Quality	++
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	++

+++ – high, ++ – middle, + – minor, - – no

Technology: Geothermal

Short description of the technology and prospects for its application in the future

- Hot geothermal fluids are converted into electric power in geothermal power stations which are similar to conventional thermal power plants.
- Of the four different types of geothermal energy resources (geo-pressured, magma, hydrothermal and hot dry rock) only hydrothermal and hot dry rock are currently being used or under development.

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- High investment costs (e.g. drilling costs)
- Geothermal energy is a good source for base load power
- Combined heat and power applications are essential due to economic reasons
- Technical restrictions (Corrosion)

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- High investment costs (e.g. drilling costs)

Technology: Geothermal			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	+
Availability of skilled staff	+	Availability of skilled staff	+
Technical maturity	+	Fuel cost	+
Standardisation of components and concepts	+	Efficiency	++
Material	++	Operating hours	++
Geographical conditions	+++	Carbon certificates	++
Climate conditions	+	Grid fees	+
Infrastructure	++	Feed-in tariffs / taxes	++
Transportation	+	Insurance	+
Licensing	++	Market situation (suppliers)	+
Production technology (e.g. mass production)	+	Quality	++
Market situation (suppliers)	+	Spare parts or any other retrofit hardware	+

+++ – high, ++ – middle, + – minor, - – no

Technology: Biogas

Short description of the technology and prospects for its application in the future

- Anaerobic fermentation of biomass (sewage sludge gas and landfill gas excluded)
- Input: energy crops, biogenic share of municipal waste, agricultural residues, food waste, residues from food processing industries
- base load, compensation of fluctuating production of other renewable

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Incentive system
- Biomass availability, quality and price
- Understanding of the microbiological metabolism
- Biogas upgrading technology

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Securing sustainable biomass production
- Process automatization
- Efficiency of microbiology
- Efficiency of biogas upgrading technology

Technology: Biogas			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	+	Staff/Labor costs	++
Availability of skilled staff	+	Availability of skilled staff	++
Technical maturity	+	Fuel cost	+++
Standardisation of components and concepts	++	Efficiency	++
Material	-	Operating hours	++
Geographical conditions	+	Carbon certificates	+
Climate conditions	+	Grid fees	+
Infrastructure	++	Feed-in tariffs / taxes	+++
Transportation	++	Insurance	+
Licensing	+	Market situation (biomass suppliers)	++
Production technology (e.g. mass production)	++	Quality	++
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	++

+++ – high, ++ – middle, + – minor, - – no

Technology: Storage general

Short description of the technology and prospects for its application in the future

There is a distinction necessary between storage of electricity directly and indirectly via different media and techniques.

The main technical solutions for storing electricity are:

- Hydro power (storage/pump storage)
- Compressed air facilities as CAES
- Batteries
- Transformation into chemical compounds
- *stored* Heat facilities

The main purpose of the storage technologies is the compensation of fluctuating production of renewables as wind and solar

Factors that influence the cost today and until 2050 (e.g. relevance of manpower for manufacturing today and 2050, mass production, material availability, resource availability)

- Incentive system
- Technical maturity
- Improvements of the cost structure

Which risk do you see for the a.m. technology on the way to 2050 and the estimated share of generation in 2050?

- Securing sustainable regulatory framework
- Necessity for enforcing drastically the R&D activities
- Mastering the cost for additional infrastructure, e.g. ´power to gas´

Technology: Storage general

Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	++	Staff/Labor costs	++
Availability of skilled staff	++	Availability of skilled staff	++
Technical maturity	+++	Fuel cost	+++
Standardisation of components and concepts	++	Efficiency	+++
Material	++	Operating hours	+++
Geographical conditions	++	Carbon certificates	+
Climate conditions	+	Grid fees	+
Infrastructure	+++	Feed-in tariffs / taxes	+++
Transportation	+++	Insurance	+
Licensing	+	Market situation (suppliers)	++
Production technology (e.g. mass production)	+++	Quality	++
Market situation (suppliers)	++	Spare parts or any other retrofit hardware	+++

+++ – high, ++ – middle, + – minor, - – no

Technology: Storage general – exemplarily for CAES			
Influencing Factors	**Influence on the CAPEX**	**Influencing Factors**	**Influence on the OPEX**
Staff/Labor costs	++	Staff/Labor costs	++
Availability of skilled staff	+++	Availability of skilled staff	++
Technical maturity	+++	Fuel cost	+++
Standardization of concepts and products	+++	Efficiency	+++
Material	++	Operating hours	+++
Geographical conditions	++	Carbon certificates	+
Climate conditions	+	Grid fees	+
Infrastructure	+++	Feed-in tariffs / taxes	+++
Transportation	++	Insurance	+
Licensing	+	Market situation (suppliers)	++
Production technology	+++	Quality	++
Market situation (suppliers)	++	Spare parts	++

+++ – high, ++ – middle, + – minor, - – no

2.2.5 Generation Technology Description – Data Sheet

In the following a systematic description in concentrated form for the most relevant generation technologies will be given. The description consists of a schematic view of the power plant concept, the key emission data, the investment figures for 2013 and 2030; in addition the key characteristic of the technology in terms of environment, maturity, economy and risk, see Annex 1.

The purpose is to give an overall summary about all data and facts used in this report.

Part III - Conclusion

3.1 Data Sources

The project ´eHighway´ is of high public interest for the issues covered in this document, the general awareness about the importance and relevance for the society is undoubted. VGB has therefore tried to deliver sound facts reliable in all terms, which means: we have used and cross-checked as many sources as possible. A particular attention was given to the energy studies of EU, DG TREN, and IEA Energy Outlook. The importance of the contribution becomes more evident when we take into consideration the clear definition of goals and targets for a low Carbon future and the evolution of the electricity demand in the upcoming years. Due to the ageing of the existing power plant portfolio, the anticipated phasing out of nuclear in different countries and the increase of energy demand in the EU-25 member states, there will be a huge additional demand on back-up respectively base load power plants until 2020 and beyond.

An evaluation of the characteristics of the different electricity production pathways is in this respect extremely important. Therefore again the portfolio of primary resources is determined by the availability of the required technologies and by the policy measures supporting the implementation of new technologies.

3.2 Lessons Learned

The evolution of the electricity technology sector in the last decades up to its actual situation contains a number of lessons that are useful in preparing the future. It is very interesting to see how these changes had the – often unspoken – intention to make electricity more available and affordable and to minimize the environmental impact of the activities.

- **A Balanced Use of Primary Sources**

The balance of the primary resources is determined by the access to primary resources, their energy density and the appropriate technology. It is an important factor in the management of two kinds of risks, namely the one of generic technology problems and the geopolitical risk; diversification is an answer. Different primary energy resources require different generation technologies, but there are a lot of synergies – one of the most striking examples of the robustness is a balanced use of primary resources. In particular the technologies for renewables can take advantage of the experience made for the conventional one.

- **Technological Innovation and Progress**

Without any doubt technology innovations have been the driving force in the electricity sector. New technologies saw the daylight, existing technologies were improved and costs were reduced in a very remarkable way. Examples were the development of gas turbines, technologies for SO_x and NO_x emissions abatement, the nuclear technologies, new high-temperature materials, the use of IT technology for better operational efficiency. The essential role played by R&D and technological development should be underlined once again. Specific situations lead to specific solutions. The system for electricity generation on an island is different from the one on the mainland. Solar systems are preferably installed in regions with high solar radiation, hydraulic systems where dams can be built and wind farms where wind is steady and abundant. The impact of access to primary resources and the efficient use of the resources are often expressed as an indicator for a secure supply of energy.

- **Contributing to Sustainable Development**

The electricity sector is fully aware about the new challenges in providing a low Carbon electricity supply; in this context it is important to have in mind the fact that the goal of a low Carbon energy supply in 2050 is mainly depending on the efforts in applying new technologies to the transport and household (= heating) sector. Electricity has the role of a leverage effect by enabling low Carbon appliances. Energy statistics of the past and reliable forecast for the future show that especially the saving of primary energy goes along with an increase of electricity production. Energy saving requires electricity. The carbon abatement strategy becomes more and more the heart of the business as well as security of supply.

3.3 Preparing the future

Under the title ´preparing the future´ two blocks are targeted:

- Potential and robustness of the technologies and their perspectives in terms of efficient use of primary resources and costs.
- Political measures (e.g. subsidies, licensing) necessary to enable an efficient implementation of these technologies, respectively their development and deployment.

Essential factors for minimizing the uncertainties of forecasts are the reliability of the data. But at the end the key question is how reliable are the data used, how accurate are the assessments taken. The robustness of the outcome in terms of the chosen criteria based on a sustainable development – environment, security of supply and affordability – has been elaborated by a comprehensive sensitivity analysis.

The facts taken for the determination of cost of electricity are based on real projects and on prices achieved in the years 2006 up to 2013. Starting from this basis the figures for 2030 and 2050 have been extrapolated on the gained R&D results, the perspectives for the future and the experience from the past.

The basic data set can be seen as not too optimistic concerning the learning effect.

In the sensitivity analysis the figures for efficiency improvements and investment costs have been varied in the ´positive´ and optimistic direction. The result is that their impact on the primary balance as well as on the technology portfolio is quite limited – it lies within the range of general uncertainties. Consequently, the conclusions of the study should be regarded as robust; they may be taken as a basis for political actions and orientation for technical development. The figures are best estimate by taking into account the different influencing factors; only for certain technologies with a high impact of geographical and meteorological conditions a range for the investment cost has given.

3.4 Main Results – Data and Graphs

Table 3 consists of the following columns: technology, lifetime, operation hours, CAPEX (balance of plant, mean regional impact), efficiency (net efficiency in terms of heat value), refurbishment (major upgrade in replacing turbine blades, pulverizer or I&C systems) and the scattering range from 2013 to 2050 as well as annual OPEX (personnel, insurance, taxes, auxiliaries, etc.) in percent of invest costs. The given technical figures represent achievable targets for the operation of the plants.

Table 3: Overview of the Cost Elements for different Technology Pathways

Levelised Costs of Electricity EURELECTRIC / VGB 2013 Edition

Technology		Life time (years)	Typical Plant Size (MW)	Operation hours (h)[1] (baseload)	CAPEX (EUR/kW) and Efficiency (%)						OPEX[14] per year as % of invest
					2013		*2030*		*2050*		
					CAPEX	Efficiency[10]	*CAPEX*	*Efficiency*	*CAPEX*	*Efficiency*	
Fossil Fuels [8]											
Gas open cycle		25	~250	6000	650	45	*650*	*45*	*650*	*45*	3.0%
Gas CCGT (advanced)		25	>400	6000	850	57	*780*	*60*	*730*	*62*	2.5%
Hard coal 600		35	~800	7500	1300	43	*1300*	*46*	*1300*	*49*	2.0%
Lignite 600		35	~800	7500	1400	41	*1400*	*44*	*1400*	*47*	2.0%
Fluidized Bed Coal		30	~400	7500	1300	41	*1300*	*44*	*1300*	*46*	2.0%
Fluidized Bed Lignite		30	~400	7500	1400	37	*1400*	*40*	*1400*	*43*	2.0%
IGCC (Lignite)		20	~400	7500	2400	45	*2300*	*50*	*2100*	*53*	2.0%
Hard coal / Lignite 700		35	~800	7500			*2100*	*50*	*1800*	*52*	2.0%
Gas CCGT + CCS		25	>400	6000			*1700*	*45*	*1700*	*48*	2.5%
Hard coal 700 + CCS (all technol		35	~800	7500			*3000*	*40*	*2700*	*41*	2.0%
HC 600 + Biomass-co-firing		30	~800	7500	1390	>45	*1300*	*47*	1300	*49*	2.0%
Nuclear											
EPR1600		40[2]	1600	7900	3300	34	*2800*	*36*	*2600*	*37*	2.0%
3rd Generation		40[2]	1600				*3800*	*38*	*3600*	*40*	2.0%
Storage											
Pumped storage		50-60	~250	2500[4]	1100-2400[5]	80	*1100-2400* [5]	*80*	*1100-2400* [5]	*80*	1.0%
Fuel Cells		12	~1	>6000	3700	79	*2500*	*80*	*2100*	*80*	2.5%
Renewables											
Run-of-river		50-60	20-250	6000	1800-2200[5),6)]	90	*1800-2200* [5),6)]	*90*	*1800-2200* [5),6)]	*90*	1.0%
Reservior / Pump		50-60	80-250	3800	1100-2400	75	*1100-2000*	*75*	*1100-2000*	*75*	1.0%
Wind onshore		25	2-3	1800	1100-1300		*1100*		*1100*		3.3%
Wind off-shore	near	25	5[12]	3200	2000-2200		*1800*		*1800*		4.3%
	far	25	5	3800	2600-3000		*2200*		*2200*		5.0%
Solar PV (roof)		15	0.005-0.5	1100	1400-2000	10-15	*1400* [7]		*1400* [7]	*up to 20* [11]	1.0%
Solar PV System		15	~30	>1100	1600-2400	10-15	*1600*		*1600*		1.0%
Geothermal		35	~30	7000	6000	10	*4900*	*10*	*3700*	*10*	2.5%
Solarthermal CSP		30	2-50	1800-2600[13]	3000-3500	8-14	*2000*		*2000*		2.0%
Biomass		30	< 25	7500	2600	~35	*2600*	*~36*	*2600*	*~38*	2.5%
Combustion Engine[9]											
small		15	< 0,20	<5000	1000	~30	*1000*	*~30*	*1000*	*~30*	10,0%
industrial		25	> 1,0	~6000	500	~42	*500*	*~42*	*500*	*~42*	6,0%

1) operation hours are determined by market conditions
2) 60 years with additional measures
3) for new plants after 2015, taking learning effects from first projects into account
4) perspective value for coming requirements due to bridging the intermittency of RES
5) large spread, depending on local conditions
6) net investment (without specific measures)
7) target figure, open to be achieved
8) CAPEX of CHP are similar; net electrical efficiency is lower, heat utilization is higher
9) no essential difference between natural and biogas investment cost
10) figures are given in operational mode
11) refer to Si crystalline
12) beyond 2030 a power output of 8 MW is possible
13) distinguish in w/ and w/o storage facility
14) covers fixed O&M costs such as maintainance, insurance etc.

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Table 4: Survey – Power Generation Technologies in the main Characteristics

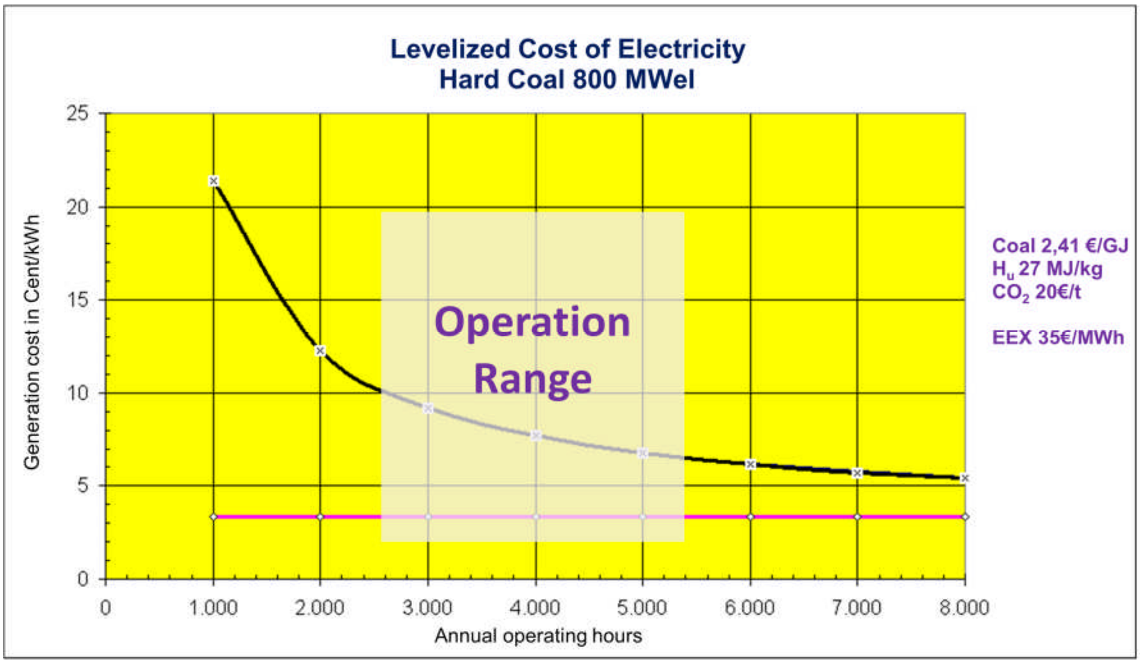
Technology		**2013**						**>2030**					
		Env	Performance		Tech	Risk		Env	Performance		Tech	Risk	
			Flex	Eco	Mat	Reg	Cost		Flex	Eco	Mat	Reg	Cost
Hard Coal	w/o CCS	+	+++	++	+++	+	+	+	+++	++	+++	+	+
	w CCS	++	+++	+	+	++	++	++	+++	+	+++	+	+
Lignite	w/o CCS	+	+++	++	+++	+	+	+	+++	++	+++	+	+
	w CCS	++	+++	+	+	++	++	++	+++	+	+++	+	+
IGCC	w CCS	++	++	+	+	++	+++	++	+++	++	++	++	++
Oxyfuel	w CCS	++	+++	+	+	++	++	++	+++	++	++	++	+
CCGT	w/o CCS	++	+++	++	+++	+	+	++	+++	++	+++	+	+
	w CCS	++	+++	++	+	++	++	++	+++	++	+++	+	+
OCGT	w/o CCS	++	+++	+	+	+	+	++	+++	+	+	+	+
	w CCS	++	+++	+	+++	++	++	++	+++	+	+++	+	+
Nuclear	H_2O, Breader, HTR	+++	+++	++	+++	++	+	+++	+++	++	+++	++	+
Hydro	run river	+++	++	++	+++	+	+	+++	++	++	+++	+	+
	reservoir	++	++	++	+++	+	+	+++	++	++	+++	+	+
	Pump storage	+++	++	++	+++	+	+	+++	++	++	+++	+	+
Wind	on-shore	+++	+	++	+++	++	+	+++	+	++	+++	++	+
	off-shore	+++	++	+	++	++	++	+++	++	++	+++	++	++
Biomass	alone	+++	+++	+	+++	+	++	+++	+++	+	+++	+	+
	co-com-bustion	++	+++	++	+++	+	+	+++	+++	++	+++	+	+
Solar	Parabolic	+++	+	+	++	++	+++	+++	+	+	+++	++	++
	Concen-trated	+++	+	+	++	++	+++	+++	+	+	+++	++	++
PV	System	+++	+	+	++	++	+++	+++	+	++	+++	++	++
	Roof	+++	+	+	++	++	+++	+++	+	++	+++	++	++
Geothermal		++	+++	+	++	+	++	++	+++	+	+++	+	++
Fuel Cells		++	++	+	+	+	++	+++	++	++	++	+	++
Micro GT		++	+++	++	+	+	+	++	+++	+++	+++	+	+
Sterling		++	++	+	+	+	+	++	++	++	++	+	+
Biogas (gas to power)		+++	+++	+	+	+	++	+++	+++	++	++	+	++
Storage ´general´		+++	+	+	+	+	+++	+++	+	++	++	+	++

Risk: +++ High (risk – impact); + Low (risk – impact)

CCGT/OCGT: Combined Cycle Gas Turbine, Open Cycle Gas Turbine
Eco: Economic viability
Env: Environmental compatibility
IGCC: Integrated Combined Cycle
Flex: Flexibility
Mat: Maturity
Reg: Regulatory framework
Tech: Technology

Table 4 shows as an overview of the main characteristics of the described generation technologies. The content is: environmental feasibility, performance split in flexibility and economics, technical maturity and risk split in regulatory and cost impact. The ranking is expressed in number of crosses.

The figures 10 a/b show the dependence of the levelised cost of electricity LCOE on the annual operating hours for hard coal and combined cycle gas turbine CCGT in the range between 2000 and 6000 hours per year. The graphs 4a and 4b show the dependence of the levelised cost of electricity LCOE on the annual operating hours for off-shore wind and photovoltaic PV between the range of 1,000 and 4,000 hours per year; limitations stemming from the different meteorological conditions have not been considered – like the duration and force of the sun in Northern and Southern Europe. It is evident that the achievable annual operating hours – in terms of equivalent full power output – is decisive for the economic viability – without and with subsidies like feed-in tariffs. The other decisive point is the system stability; i.e. the balance between the different variable and dispatchable generation technologies and the balance between demand and supply.



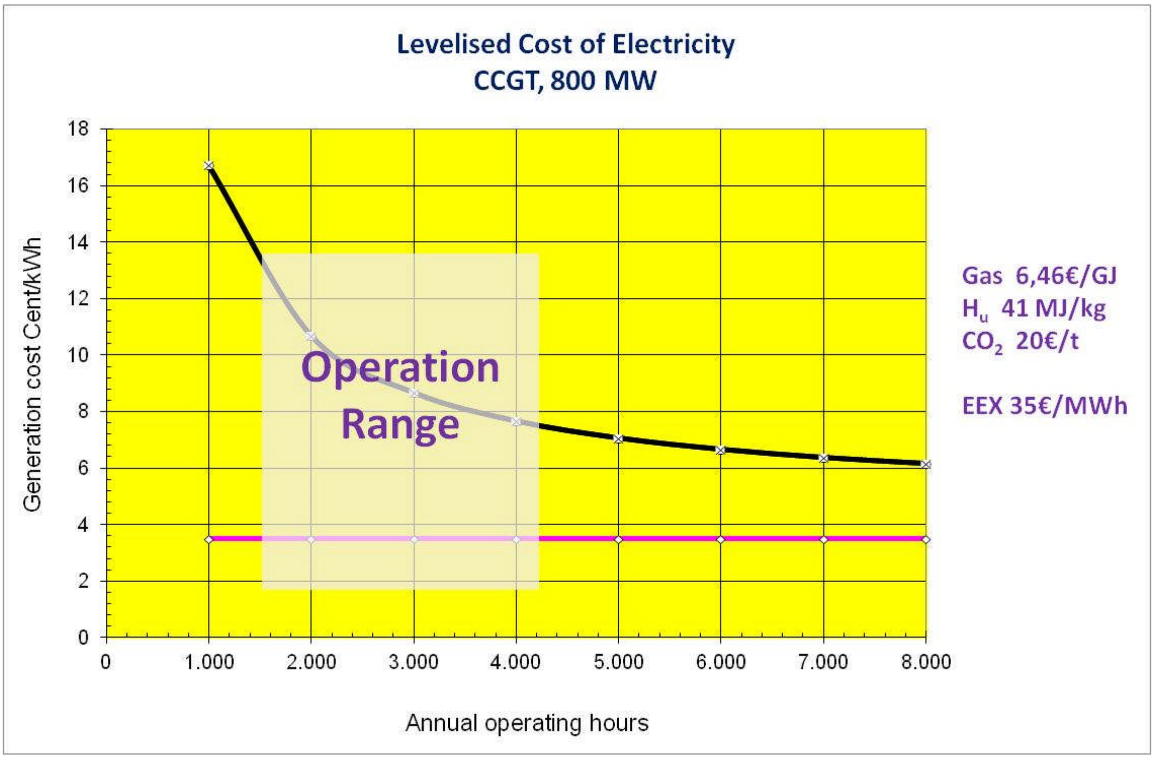
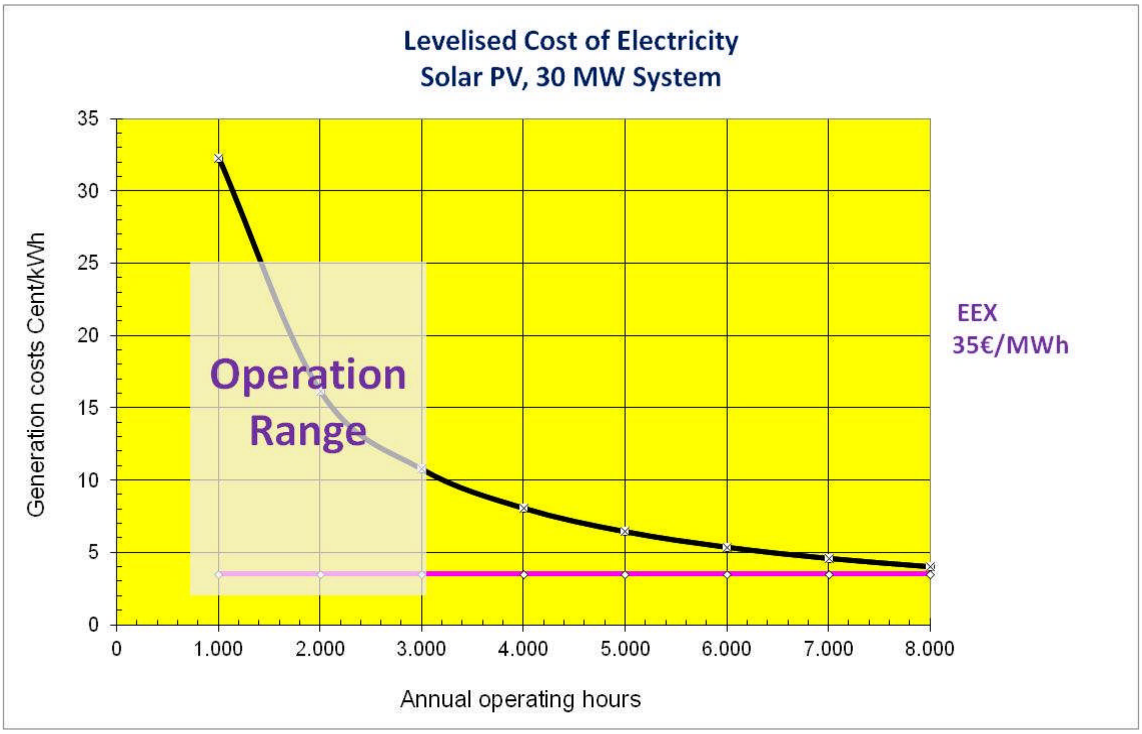


Figure 10a/b: relation of LCOE to operating hours Hard Coal, CCGT



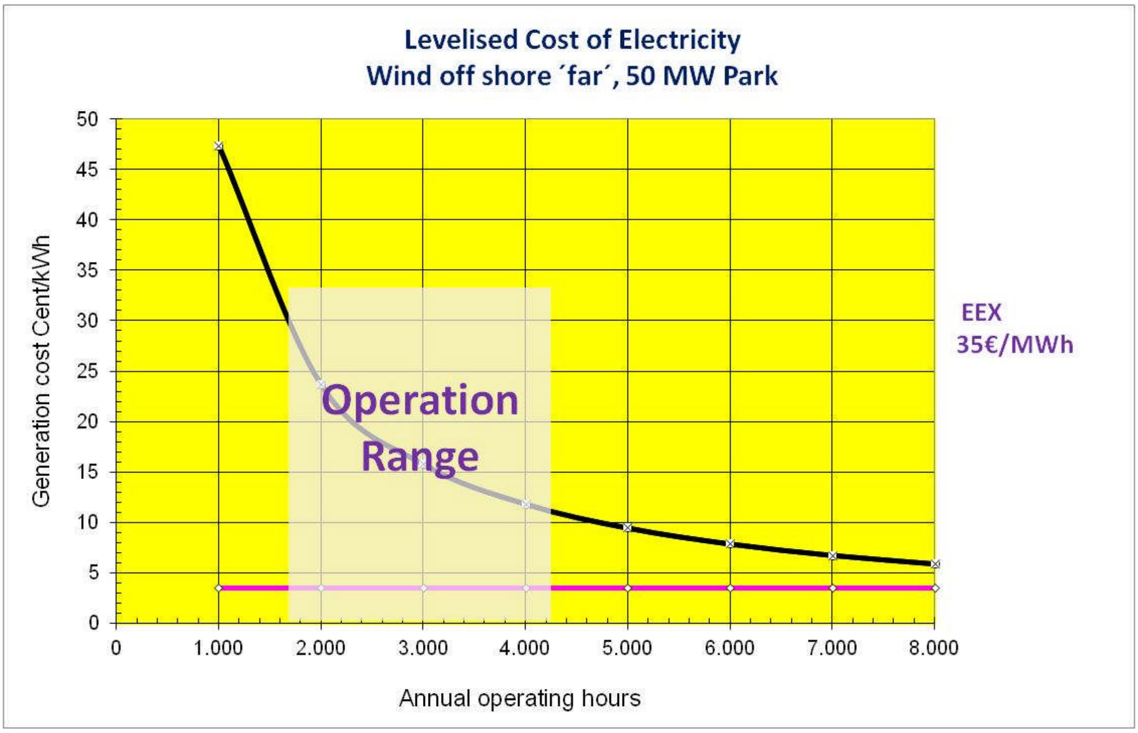


Figure 11a/b: relation of LCOE to operating hours Solar PV, Wind off-shore

3.5 Sensitivity – robustness of assessments for technology forecast

No doubt any forecast for the future is inseparably linked with uncertainties and limitations by laws of nature or shortage respectively limited access to primary resources. But at the end the key question is how reliable are the data used, how accurate are the assessments taken. The robustness of the outcome in terms of the chosen criteria based on a sustainable development – environment, security of supply and affordability – is given by a comprehensive sensitivity analysis. The facts taken for the determination of cost of electricity are based on real projects and on prices achieved in the years 2013 and 2006. Starting from this basis the figures for 2030 and 2050 have been extrapolated on the gained R&D results, the perspectives for the future and the experience from the past. The basic data set can be seen as not too optimistic concerning the learning effect; it is in line with the outcome of the working group dealing with generation technologies within the EU ´ZEP´ technology platform. In the sensitivity analysis the figures for efficiency improvements, investment costs have been varied in the ´positive´ and optimistic direction. The result is that the impact on the balance in use of primary resources as well as technologies is quite limited in showing no major changes – within the general uncertainties. This reflects also the impact of global risks in terms of fuel prices. The whole data set for different technologies builds the input for the scenario analysis concerning the correlations between demand, supply technologies and policy measures. Consequently the conclusions are robust and can be taken as a basis for political actions and orientation for technical development.

3.6 Policy measures – Actions

The move towards more competition, asks for some initiatives. The objective should be to keep the sector on the track of sustainability and robustness; meaning for the supply block incentives for innovation/new technologies.

A much-debated item is the security of supply. As we have seen, diversification in primary energy sources and in technologies has been one of the cornerstones of the robustness of our system.

Activities on R&D, formerly often considered as a normal societal duty, have to be seen now under market constraints. Choices are to be made in order to create an innovation friendly atmosphere for ambitious and future oriented R&D energy projects. The role of subsidies is to enhance the technology development by a leverage effect; the essential criteria is: they have to be market-driven. The electricity generation sector is extremely capital-intensive. That capital should be available on the markets at attractive conditions. In order to keep the risk-premium sufficiently low, a stable institutional framework is essential. The key requirements in terms of policy measures are:

- Coherent regulatory framework
  The regulatory framework covers two major topics: environmental legislation and market rules. Both are decisive for a sustainable development taking into the account the time and money needed for implementing new technologies coping with the challenges given.

- Consistent deployment strategy
  It is a matter of fact that the transfer process of R&D results into industrial/commercial application takes too much time and money due to barriers of uncertainty and risk. The core intention is to establish a deployment strategy removing the barriers as they are identified. One of the key barriers is unstable regulatory conditions beyond the risk of entrepreneurial activities. A lack of market-driven incentives covers the unavoidable risks of the implementation of new technologies. In the end improving the public acceptance is a task for all stakeholders. By creating market-driven incentives like a balanced Emission Trading Scheme complemented by a suitable risk coverage model could be a starting point for a process of communication and transition.

3.7 Summary

An analysis of the achieved results shows, that there is basis for ´robust´ conclusions. On a long term nuclear is – beyond the question of public acceptance – far most the most economical technology for supply. For the renewable resources one can see an improvement of the cost figures. Nevertheless one should have in mind that there are limitations in fuel supply concerning biomass, limitations in harvesting wind energy referring on the external costs. But for sure the renewables have an important place in future power supply. Concerning fossil primary resources the results make clear that at reasonable prices for CO_2 certificates it is economical more feasible to invest in CO_2 free technologies instead to spend money for certificates. The time line is beyond 2030.

Finally, one can state:

- There will be a broad portfolio of technologies suitable for the requirements of climate protection, security of supply and competitiveness. The broad portfolio is the outcome of different options for the use of primary resources and the amount of money needed to establish the technologies.
- Prerequisite for the implementation of these new technologies are balanced policy measures consisting of a coherent regulatory framework and a consistent deployment strategy.
- The impact on the gross domestic product (GDP) will be moderate if risks are well spread by using all different resources – primary fuel, financial and human resources – minimizing the impact of technologies on cost of electricity and consequently the impact on GDP in terms of affordability and climate protection. This is one of the conditions for a sustainable development in the future meeting with the challenges of climate change, saving our resources and maintaining economic welfare.