Electrical Power Vision 2040 for Europe

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Convention of National Associations of Electrical Engineers of Europe

ELECTRICAL POWER VISION 2040 FOR EUROPE

A DOCUMENT FROM THE EUREL TASK FORCE
ELECTRICAL POWER VISION 2040

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Electrical Power Vision 2040 for Europe

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Full version

Table of contents

Table of contents **5**

List of figures **9**

List of tables **12**

1. Introduction and motivation **13**

2. European power generation in the past **17**
- 2.1 Development of power generation in the last two decades in EU27+ 17
- 2.2 The role of the renewables in Europe today 20
- 2.3 Characteristics in some particular countries 20

3. Changing role of electric power **25**
- 3.1 State of the final energy and final electricity consumption 25
- 3.2 Driving factors for switching from fossil to electric power 26
- 3.3 Influence of renewable energy 27
- 3.4 Changing role of electricity in the transport sector 27
- 3.5 Changing role of electricity in the residential sector 30
- 3.6 Future role of security of supply 32

4. Environmental, economic and political requirements on the supply security of electrical power. **35**
- 4.1 Green-house gas (GHG) reduction goals 35
- 4.2 Implication of Liberalization 36
- 4.3 Electricity price policy and price control 36
- 4.4 Dependency reduction from suppliers of primary energy from outside the EU 27 37
- 4.5 Efficiency improvement to reduce costs and to protect resources 38

5. European electrical power demand in the next decades **41**
- 5.1 Development of power demand from 1990 to 2008 41
- 5.2 Estimation of the power demand until 2050 43
  - 5.2.1 Method of estimation 43
  - 5.2.2 Estimation in the various application areas 45

6. Options for future bulk power transport and supply security of power **51**
- 6.1 Introduction 51
- 6.2 The Transmission Grid in Europe – Current Situation and Challenges 51
  - 6.2.1 Historic Evolution of the UCTE / ENTSO-E Grid 51
  - 6.2.2 Transmission Challenges Driven by Electricity Trade 52
  - 6.2.3 Transmission Challenges Driven by the Production Side 52
  - 6.2.4 Transmission Challenges Driven by Demand Side and Developments in the Distribution Grid 53

6.2.5 Conclusion 54
6.3 Market Options for the Facilitation of Future Bulk Power Transport 54
6.3.1 Cross-border Trading and Market Coupling 54
6.3.2 Cross-border balancing 54
6.4 Technological Options for the Facilitation of Future Bulk Power Transport 55
6.5 Case Study 57

7. Options for future power production 61
7.1 Fossil with CCS including combined cycle plants 61
7.1.1 Introduction 61
7.1.2 CO_2 capture 62
7.1.2.1 Post-Combustion 62
7.1.2.2 Pre-Combustion 63
7.1.2.3 Oxyfuel 63
7.1.2.4 Post-Combustion in CCGTs 64
7.1.2.5 Flexibility of plants with CO_2 capture 64
7.1.3 CO_2 transport 65
7.1.4 CO_2 storage & disposal 65
7.1.5 Status and expectations of CCS 66
7.2 Nuclear 67
7.2.1 Generations of Nuclear Power Plants 67
7.2.2 Safety 69
7.2.2.1 Radioactive inventory 69
7.2.2.2 Safety barriers 70
7.2.3 Safety of currently operated plants 70
7.2.3.1 Generation II as initially designed 70
7.2.3.2 Generation II today 71
7.2.3.3 Generation III 72
7.2.3.4 Generation IV 75
7.2.4 Fuel sustainability 76
7.2.4.1 Generation of new fissile material 76
7.2.4.2 Transmutation 78
7.2.4.3 Reprocessing as a complement to generation IV 78
7.2.4.3.1 Hydro-metallurgical processes 78
7.2.4.3.2 Pyro-metallurgical processes 79
7.2.4.4 Safety 79
7.2.5 Other concepts outside generation IV 80
7.2.5.1 Travelling wave reactor (TWR) 80
7.2.5.2 Accelerator Driven Systems (ADS) 81
7.2.6 Summary 82
7.3 Wind 83
7.3.1 Wind energy development and outlook in the European Union 83
7.3.1.1 Regions with poor wind conditions, repowering 84

7.3.1.2 Offshore wind 84
7.3.2 Grid- Integration of offshore wind plants 86
7.3.3 Innovations and trends 87
7.4 Geothermal 89
7.4.1 Introduction 89
7.4.2 Energy potential 90
7.4.3 Geothermal energy use 90
7.4.4 Geothermal energy systems 91
7.4.4.1 Surface geothermal energy 91
7.4.4.2 Hydrothermal systems 92
7.4.4.3 Petro thermal Systems 93
7.4.4.4 Use period of geothermal systems 93
7.4.5 Exploitability of various geothermal systems 94
7.4.6 Exploration 95
7.4.7 Environmental aspects 96
7.4.8 Production costs 97
7.5 Photovoltaics 97
7.5.1 Introduction 97
7.5.2 Potential of solar energy 97
7.5.3 The photoelectric effect 98
7.5.4 How solar cells work 99
7.5.5 Solar Cell Types 100
7.5.5.1 Silicon cells 100
7.5.5.2 Solid state solar cells 101
7.5.6 Availability of basic solar cell materials 101
7.5.7 Availability of photovoltaics 101
7.5.8 Impact of photovoltaic systems on the electricity network 103
7.5.9 Environmental impact 105
7.5.10 Energy payback time (energetic amortization) 105
7.6 Concentrated Solar Power 105
7.6.1 Introduction 105
7.6.2 Direct Solar Irradiation - DNI 106
7.6.3 CSP Solar Receiver Technologies 107
7.6.4 CSP Conversion Technologies 108
7.6.4.1 Steam Cycle with Storage 108
7.6.4.2 Integrated Solar Combined Cycle (ISCC) 109
7.6.4.3 Solar-Driven Gas Turbine Combined Cycle (SD-GTCC) 110
7.6.4.4 Cost Aspects of CSP 110
7.6.4.5 Current Situation and Outlook of CSP 111
7.7 Biomass technologies for power plants 112
7.7.1 Introduction 112
7.7.2 Co-firing concepts 113

7.7.3 CHP concepts 113
7.7.4 Integrated gasification combined cycle 114
7.7.5 Waste installation 114
7.8 Hydro power 115
7.8.1 Introduction 115
7.8.2 Hydroelectric power production 115
7.8.3 Function of hydroelectric power plants 116
7.8.4 Turbines of hydroelectric power plants 116
7.8.5 Availability of hydropower 119
7.8.6 Environmental impact 119
7.8.7 Investment costs 120
7.8.8 Electricity production costs 120
7.8.9 Expansion potential of hydropower 120
7.8.10 New technologies 120

8. Storage technology options 123
8.1 Introduction 123
8.2 Need for storage systems and requirements 123
8.3 Characterization of storage systems 125
8.4 Storage technologies 125
8.5 Economic assessment 129
8.6 Alternatives to energy storage systems 131

9. Option for future decentralized micro grid energy structures 133
9.1 Driving factors 133
9.2 Photovoltaics 134
9.3 Solar Thermal 136
9.4 Micro grid management 136
9.5 Strategic analysis of micro grids 137

10. Integration of renewables, need for the enhancement of system flexibility 139
10.1 Scenario Germany 140
10.2 Options for integration renewable energy and enhancement of the system flexibility 146

11. Scenarios for the future power demand and generation mix in EU27+ .149
11.1 Methodology and data sources 149
11.2 Main assumptions 150
11.3 The LoREN-Scenario 150
11.4 The HiREN Scenario 154
11.5 Comparison of the scenarios 157

12. Outlook for a future power supply systems 163

13. Conclusions and recommendations 169

13.1 Conclusion from the scenarios 169
13.2 Recommendations and need for action 170

14. Appendix 173
14.1 Appendix: Daily demand for warm water 173
14.2 Appendix: Power consumption development from 1990 – 2008 in TWh ...173

15. Literature 177

List of figures

Figure 1: Development of the crude oil price 13
Figure 2: Development of the average surface temperature of the earth 14
Figure 3: Power Generation of EU27+ in TWh 17
Figure 4: Power generation by primary energy in 1990 in TWh and %.... 18
Figure 5: Power generation by primary energy in 2008 in TWh and %.... 18
Figure 6: Installed power capacities in 2008 in GW and %.... 19
Figure 7: Development of renewables in EU27+ in TWh 20
Figure 8: Power generation of the Top5 countries in TWh 21
Figure 9: Installed power of the TOP5 countries in GW.... 22
Figure 10: Main sectors of energy end-use in EU-27 in 2008 [3.1].... 25
Figure 11: Sectors of final electricity consumption in EU-27 in 2008 [3.1] 25
Figure 12: Specific energy demand of cars with combustion and electric drives 28
Figure 13: Specific CO2-emissions of power train concepts.... 29
Figure 14: Reduction potential of total energy demand in the private sector 31
Figure 15: Changing electricity demand of households inclusive car 32
Figure 16: Power consumption in EU27+ in TWh 42
Figure 17: Power demand in the EU27+ top5 countries in 1990 and 2008 in TWh .. 43
Figure 18: Methods of estimation 44
Figure 19: Industry power consumption in TWh 45
Figure 20: Transport power consumption in TWh. 46
Figure 21: Residential power consumption in TWh 47
Figure 22: Services power consumption in TWh 48
Figure 23: Overall power consumption in TWh in EU27+ (conservative scenario) ... 48
Figure 24: Power consumption in TWh in EU27+ (progressive approach) 49
Figure 25: Connection of systems 56
Figure 26: Tower images of AC and DC lines.... 57
Figure 27: Annual Average Line Loading in 2050 (Base Case) 58
Figure 28: Annual Average Line Loading in 2050 (AC Expansion).... 59
Figure 29: Annual Average Line Loading in 2050 (HVDC Expansion).... 60
Figure 30: Overview of different CO2 capture methods in power plants.... 62
Figure 31: Cost increase and efficiency penalty; summary 64

Figure 32: CO2 pipeline network in 2050, assuming joint international optimization. Total amount of CO2 captured and stored: 1145 Mt/y. 66
Figure 33: In-vessel molten core retention and ex-vessel core catcher in Gen III systems. 73
Figure 34: Passive systems applied in Gen III for the most important safety functions 74
Figure 35: Reactor generations in the coordinate system "sustainability" and "safety" 76
Figure 36: Scheme of a closed nuclear fuel cycle 77
Figure 37: Conversion process in fast reactors as source of long lasting fuel resources.. 77
Figure 38: Additional generation of a 2 MW wind plant in South Germany due to the increase of the hub height and rotor diameter 84
Figure 39: Concept of the European offshore – super-grid in North Europe............. 86
Figure 40: Development of the size of the wind power plants 87
Figure 41: Gearless Siemens SWT-6.0 wind plant. Comparison of the 154 m rotor with the Airbus A 380.. 88
Figure 42: Temperature profile of the Earth.. 90
Figure 43: Geothermal pioneers (Lardello, Italy1903) 91
Figure 44: Geothermal energy use 91
Figure 45: Geothermal Power Plant (Heinze et al. (2003) 92
Figure 46: Microseism 95
Figure 47: Drilling 96
Figure 48: Average solar irradiance.. 97
Figure 49: Solar Electricity Potential in European Countries 98
Figure 50: The Standard c-Si Solar Cell Structure (Fraunhofer ISE)........................ 99
Figure 51: Crystalline Silicon Cell and Module (Fraunhofer ISE)............................100
Figure 52: An example: The monthly energy production in northern Germany in 2008 102
Figure 53: Solar energy-, power- and global radiation diagram on an ideal day......102
Figure 54: This is contrasted by a diurnal cycle of a photovoltaic area system with a power of 21 MV on a day with medium sky cover..................................103
Figure 55: Electricity demand, VDEW daily load curve in the winter 104
Figure 56: Direct Normal Irradiation (DNI) for the Mediterranean region. 106
Figure 57: CSP technology families..107
Figure 58: Principle of conversion technology from solar heat to electricity. 108
Figure 59: Basic set up of power plant with molten salt storage. 109
Figure 60: Illustration of increased value of CSP plants with storage 109
Figure 61: Example of a hybrid concept, the combination of solar heat to heat up feedwater in a CCGT. This concept is referred to as Integrated Solar Combined Cycle (ISCC) 110

Figure 62: Set up of a solar-driven gas turbine complemented with a steam cycle. CCGT. The RHS of the figure shows the “replacement” of the combustion chamber.. 110
Figure 63: Specific-cost comparison of different technologies. 111
Figure 64: The principal direct and indirect co-firing routes 113
Figure 65: Hydropower, IEA 115
Figure 66: Hydraulic system, Kraftwerke Oberhasli 116
Figure 67: Kaplan turbine, Wikipedia 117
Figure 68: Francis turbine, Wikipedia 118
Figure 69: Pelton turbine, Wikipedia 119
Figure 70: Hydropower plant Laufenburg, Switzerland 121
Figure 71: Comparison of storage systems for long-term storage (class A) 130
Figure 72: Comparison of storage systems for load-levelling (class B) 130
Figure 73: Electric power of pumped storage hydro plants in GW and relative power in % related to installed RES 134
Figure 74: Evolution of PV by the end-use sector 135
Figure 75: Typical profiles PV generation in an energy active settlement 135
Figure 76: Residual balancing power to the grid 135
Figure 77: Need for action for the improvement of the system-flexibility in selected European countries in the time period 2020-2025 140
Figure 78: Residual load in Germany, 2020, Scenario with 40% share of renewable generation 142
Figure 79: Energy mix for 2 selected weeks. a) Scenario 2009, b) Scenario 40% of renewable generation 143
Figure 80: Full load hours and number of starts for different bands of residual load. Scenario with 40% of renewables in the generation mix. Comparison 2010-2020 144
Figure 81: Gradients of the residual load changes over 1 hour, comparison of the year 2010 and 2020: scenario with 40% share of renewables in the generation mix, ...145
Figure 82: Opportunities for the enhancement of the flexibility in the electricity supply 147
Figure 83: Length of the edge of a cube containing an energy equivalent of 1 h generation from wind and solar power in HiREN scenario in 2050. 148
Figure 84: Generation mix in TWh in 2050 for EU27+ (LoREN scenario) 151
Figure 85: Installed Power in GW in 2050 for EU27+ (LoREN scenario) 152
Figure 86: CO2 emissions in Mio t in 2050 for EU27+ (LoREN scenario) 153
Figure 87: Investment costs in power plant in bill. € until 2050 (LoREN scenario) ..154
Figure 88: Generation in TWh in 2050 for EU27+ (HiREN scenario) 155
Figure 89: Installed power in GW in 2050 in EU27+ (HiREN scenario) 156
Figure 90: CO2 emissions in Mio t in 2050 for EU27+ (HiREN scenario) 156

Figure 91: Investment costs in power plant in bill.€ until 2050 (progressive scenario) 157
Figure 92: Comparison of generation mix..158
Figure 93: Comparison of the installed power mix..159
Figure 94: Comparison of investment costs in bill.€ for 2010-2050 160
Figure 95: Estimation of the CO_2 emissions in mill.t in 2030 and 2050...................161
Figure 96: New structure of the power generation scheme 164
Figure 97: Structure of a future power supply system (Origin: Siemens).................165
Figure 98: Synergies between the infrastructures for electricity, heat and mobility .166
Figure 99: EU27 import-dependency of fossil fuels 166

List of tables

Table 1: Urbanization rate in per cent of total population in developing countries (D.C.) and industrialized countries (I.C.) 26
Table 2: CSP technology families..107
Table 3: Overview on storage applications and suited storage technologies 126
Table 4: Peak load and installed power...159
Table 5: Summarizes the result of the scenarios with regard to the EU 2050 main goals 169

1. Introduction and motivation

Energy prices are rising from year to year in a speed that is much faster than the general inflation rate. Considering the oil price this increase was over 10% p.a. in the last 15 years (figure 1). More and more people are worried about our primary energy resources and their availability. Some experts say the turning point of the exploration-versus- consumption-rate is already reached.

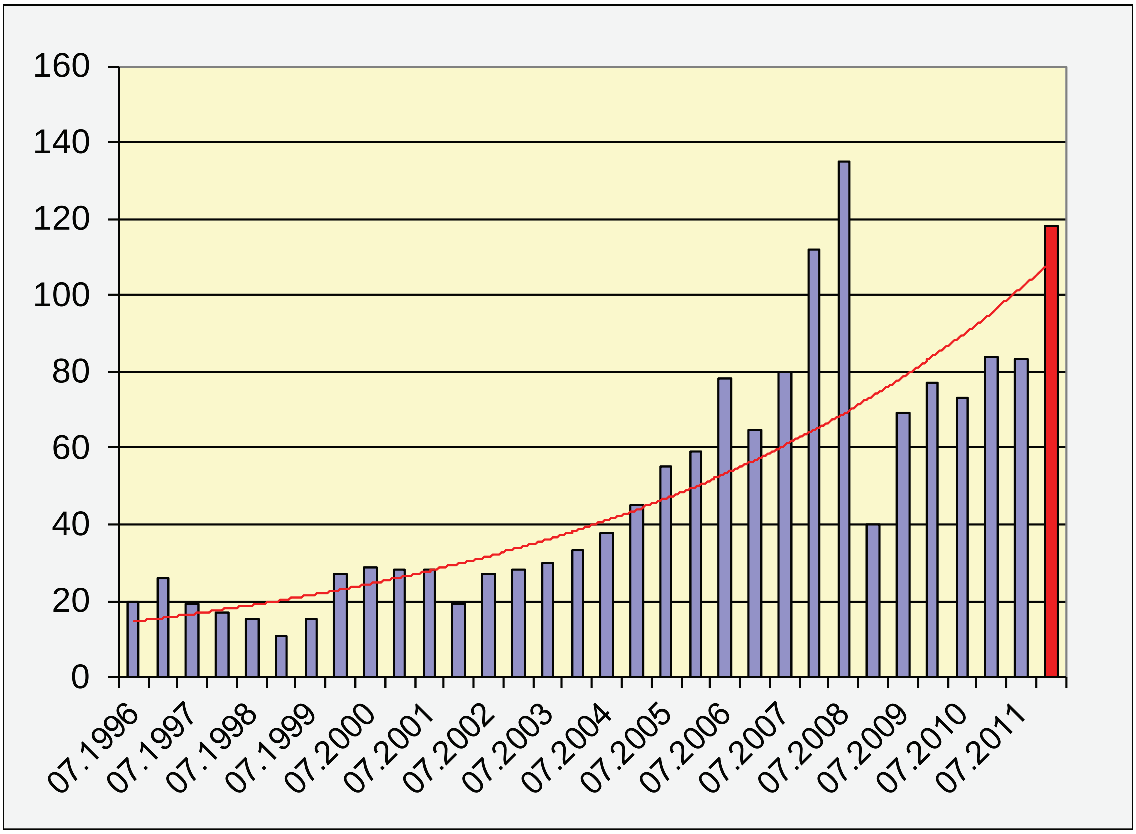

Figure 1: Development of the crude oil price

Parallel to the resource scenario the climate scenario is also seen as an issue. The meteorologists found out that the average surface temperature of the earth is rising and will have disastrous consequences on our lives if not stopped. It is assumed that the greenhouse gas (GHG) emissions are the cause for the abnormal temperature increase (Figure 1).As consequence of the above mentioned phenomenon the national and international political bodies are discussing the “energy problem” and are working on possible solutions.

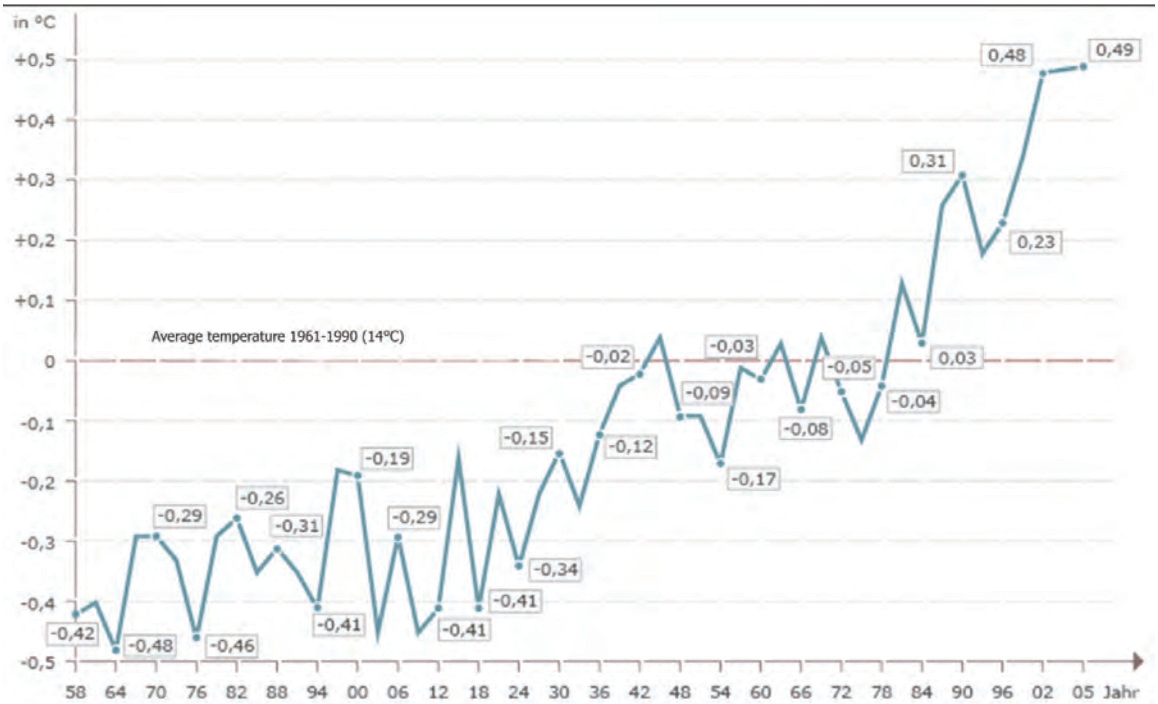

Figure 2: Development of the average surface temperature of the earth

In March 2007 the EU Heads of State and Government set a series of demanding climate and energy targets to be met by 2020, known as the "**20-20-20" targets"** [1.1]. These are:

- A reduction in the EU greenhouse gas emissions of at least 20% below 1990 levels
- 20% of EU energy consumption to come from renewable resources
- A 20% reduction in primary energy use compared with projected levels in 2020 to be achieved by improving energy efficiency.

The EU leaders also offered to increase the EU's emissions reduction to 30%, on the condition that other major emitting countries in the developed and developing world commit to do their fair share under a global climate agreement. United Nations negotiations on such an agreement are still on going.

On 10 November 2010, the European Commission has set up "**Energy 2020 - A strategy for competitive, sustainable and secure energy**" [1.2]. The strategy defines the energy priorities for the next ten years and sets the actions to be taken in order to tackle the challenges of saving energy, achieving a market with competitive prices and secure supplies, boosting technological leadership, and effectively negotiate with our international partners.

And finally on 15 December 2011, the European Commission communicated the "**Energy Roadmap 2050**" [1.3]. The EU is committed to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050 in the context of necessary reductions by developed countries as a group. In the Energy Roadmap 2050 the Commission explores the challenges posed by delivering the EU's decarbonisation objective while at the same time ensuring security of energy supply and competitiveness**.** The Energy Roadmap 2050 is the basis for developing a long-term European framework together with all stakeholders.

Having the EU energy strategy and target in mind a task force of EUREL started work in 2010 to develop concepts and scenarios how to implement the European energy goals. EUREL is the Convention of National Societies of Electrical Engineers of Europe. It was founded in Switzerland in 1972. Its aim and objects are to facilitate the exchange of information and to foster a wider dissemination of scientific, technical and related knowledge relevant to electrical engineering. In 2010 the special task force “Power Vision 2040 for Europe” was set up to investigate the future power supply of Europe. The task force´s experts are coming from utilities, industry and universities from various European countries. It has prepared this study on the electrical power supply for Europe for the next decades until 2050.

The study analyses in a first step the electrical power demand in the EU27-countries plus Croatia, Norway and Switzerland (EU27+) until 2050. This forecast includes the expected efficiency improvement potentials in the electrical devices and processes, it considers new applications like e-cars, heat pumps and other new consumers and it incorporates the trend in power demand of the recent years. The analysis comprises the development in industry, transportation, households and services sector.

In a second step the study describes the available technologies to produce electricity with a strong focus on renewable and their integration challenges. But also traditional technologies like water, fossil and nuclear source are investigated.

Finally the study shows in three scenarios the possible power generation mix, the resulting CO2 emissions and the investment costs for the transformation of the electrical power industry until 2050 taking in account the goals of the EU commission.

The study gives conclusions and recommendations for the future European power supply system at the end of the document.

2. European power generation in the past

2.1 Development of power generation in the last two decades in EU27+

The development of power generation in Europe followed mainly the demand increase in the residential and service sector as well as the development of the European Industry. The following figures reflect the situation in the 27 states of the European Union as well as in Norway, Switzerland and Croatia, which is appreviated in the following as EU27+. Croatia is included since it will be a member of the EU very soon. Norway and Switzerland are linked very tightly into the European electricity system. Although the primary energy mix is quite different in the various member states the backbone of the power supply in EU27+ is coal, gas, nuclear and water. Until today oil and renewables do not play a significant role. This may differ partly in certain countries – i.e. Germany with regard to the renewables – but is overall valid. Figure 2 shows the increase of power generation from 1990 till 2008. All figures are based on the database of EUROSTAT. The increase was in this period 1, 6 % per annum or 37% for nearly two decades.

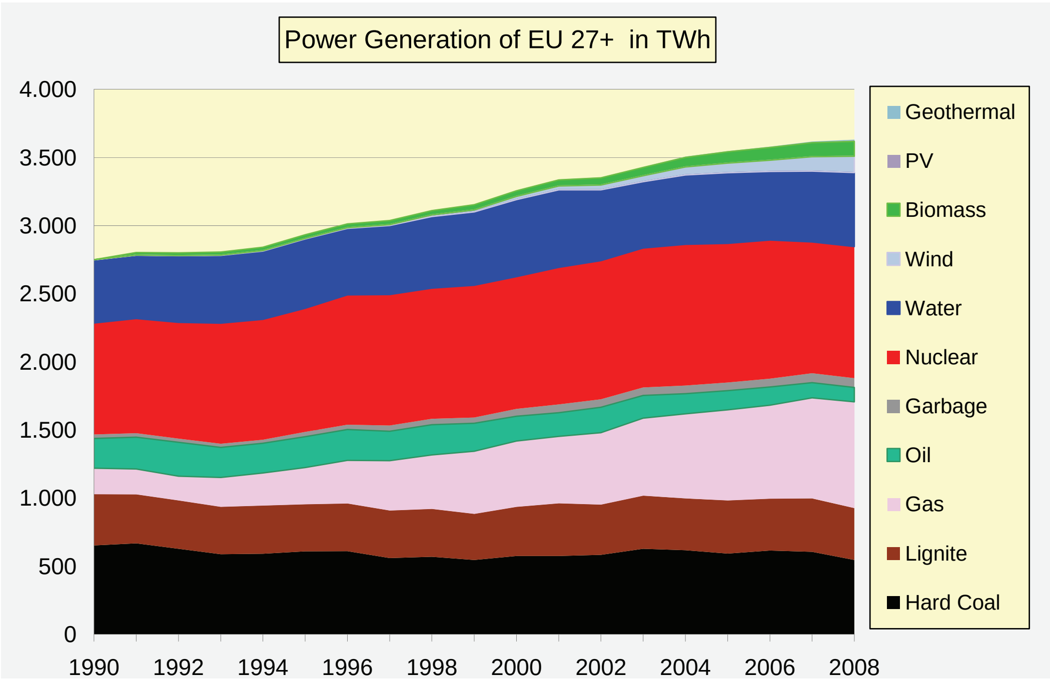

Figure 3: Power Generation of EU27+ in TWh

While the use of oil decreased by 51%, the gas fired power station output boosted by 311%. Coal contributed nearly the same amount to the energy mix in 1990 as in 2008, nuclear and water increased only slightly by 17%. The renewables started in 1990 practically with no contribution.

The power mix in1990 and in 2008 is displayed in figure 4 respectively in figure 5. The total output of the power stations in EU27+ was 3598 TWh in 2008 coming from

2770 TWh in 1990. While nuclear, coal and gas generated in 2008 approximately a quarter of the

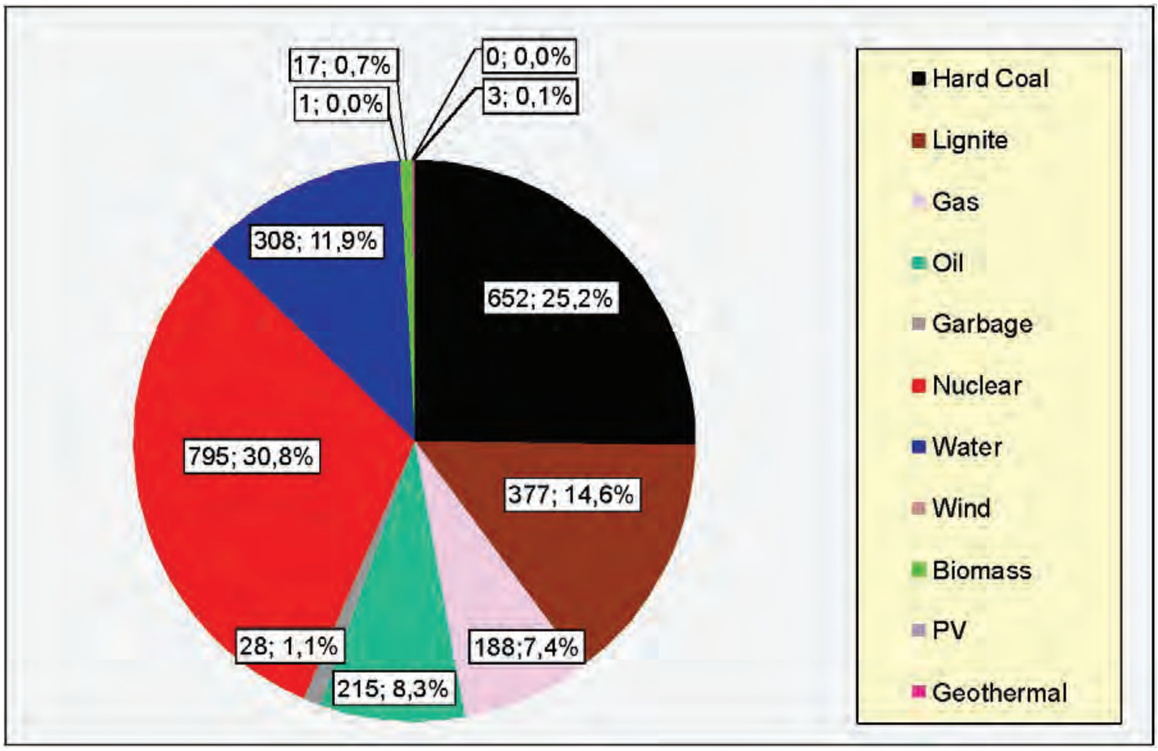

Figure 4: Power generation by primary energy in 1990 in TWh and %

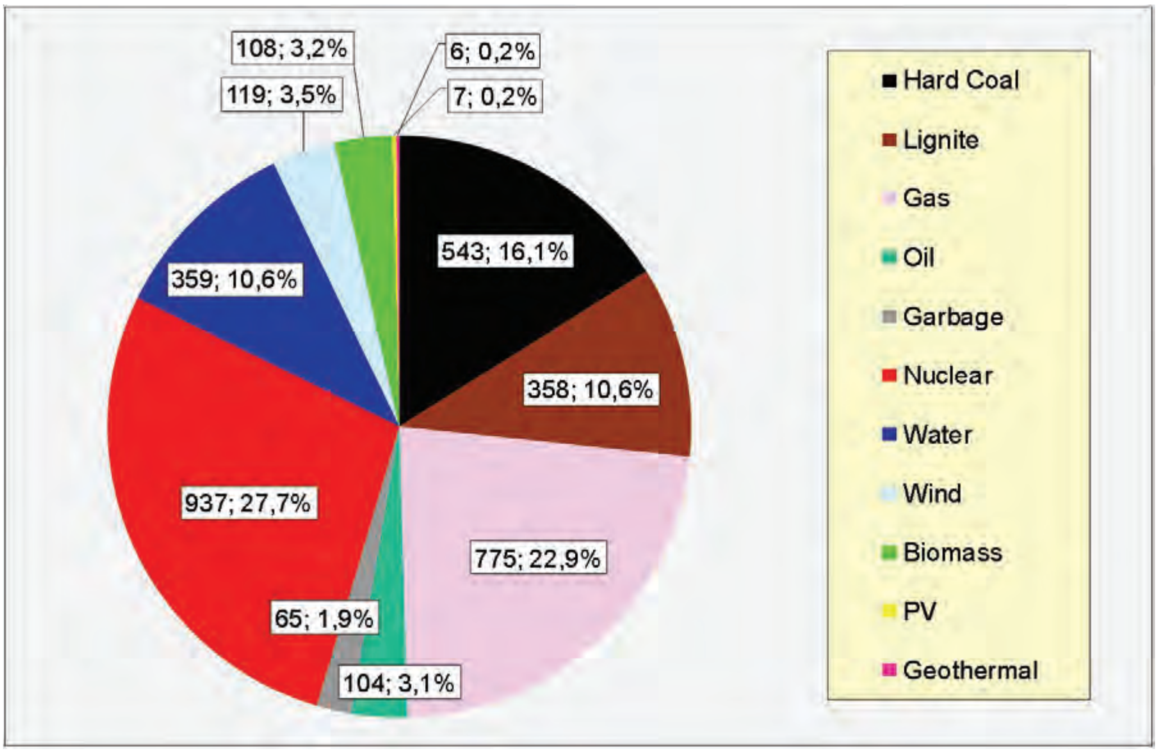

Figure 5: Power generation by primary energy in 2008 in TWh and %

total power supply, water delivered about 10%, all others together summed up to 12%. These overall numbers differ partially very much in the various member states. Chapter 2.3 gives an insight in the situation of the TOP5 member states.

Because of the very different operating hours per annum of the various types of power plants, the mix of the power plant capacities in GW shows a different picture than the mix of the generated TWh´s (figures 5 and 6). Nuclear power stations generated 27 % of the total power, but had only a capacity of 16% of the total. These numbers for coal are 27% resp. 17%. The gas based generation and the installed capacity is with 23% nearly identical. The oil power plant fleet shows a very different picture. The generation is only 3%, the installed capacity is16% of the total. Most of the oil power stations are not anymore in operation or are in standby. They are substituted by new, much more efficient gas power stations.

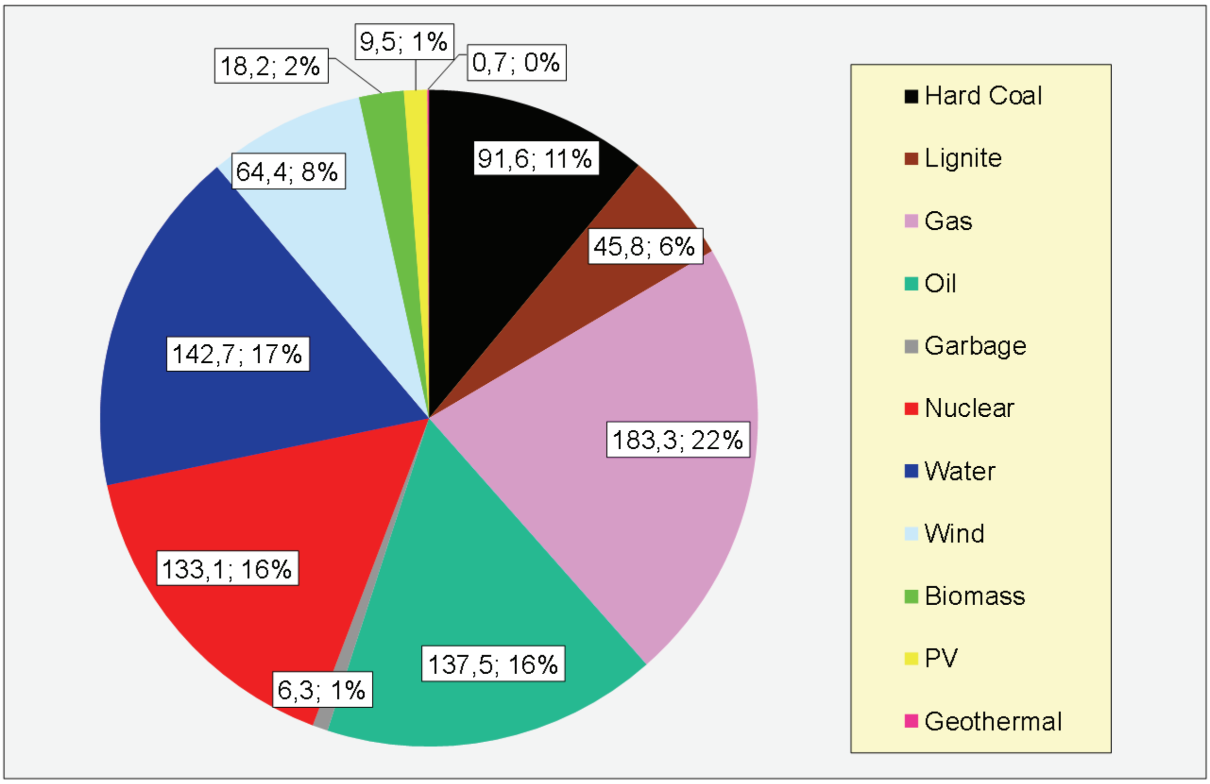

Figure 6: Installed power capacities in 2008 in GW and %

For renewables the situation is principally different. The operating hours depend on the availability of the natural resources water, wind and sunshine and cannot be independently controlled by the demand except for the bio mass. Therefore the full load operating hours are relatively low. An exception is the biomass. The relation of the shares of the total generation to the shares of the total installed power capacities is 11% to 17% for water, 3,5 % to 8% for wind, 0,2% to 1% for photovoltaic power generation while for biomass generation the relation is 3,2% to 2(!). This must be considered when the renewables will be expanded in the future.

2.2 The role of the renewables in Europe today

Figure 7 shows the fast increase of the renewable power production with the exception of water which stays nearly at the same level While in 1990 the generation of electricity by wind, biomass, photovoltaic and geothermal resources was basically negligible, the contribution in 2008 to the total generation was already more than 7% or nearly 250 TWh.

Wind and biomass were the main contributors of the renewable primary energies. Especially the investment in wind turbines rose significantly in the last two decades and is still rising on high level. The bulk amount of the generated 119 TWh came in 2008 from Germany and Spain. While the increase in wind generation started already at the end of the 90´s the start of the PV rally began in the middle of the last decade.

Geothermal resources are significantly used until today only in Italy. In some the other member states there are pilot projects, but until now there is practically no contribution to the power supply. This may change when the technology is more mature and cost effective. The potential of the geothermal energy may play in the future a much more important role.

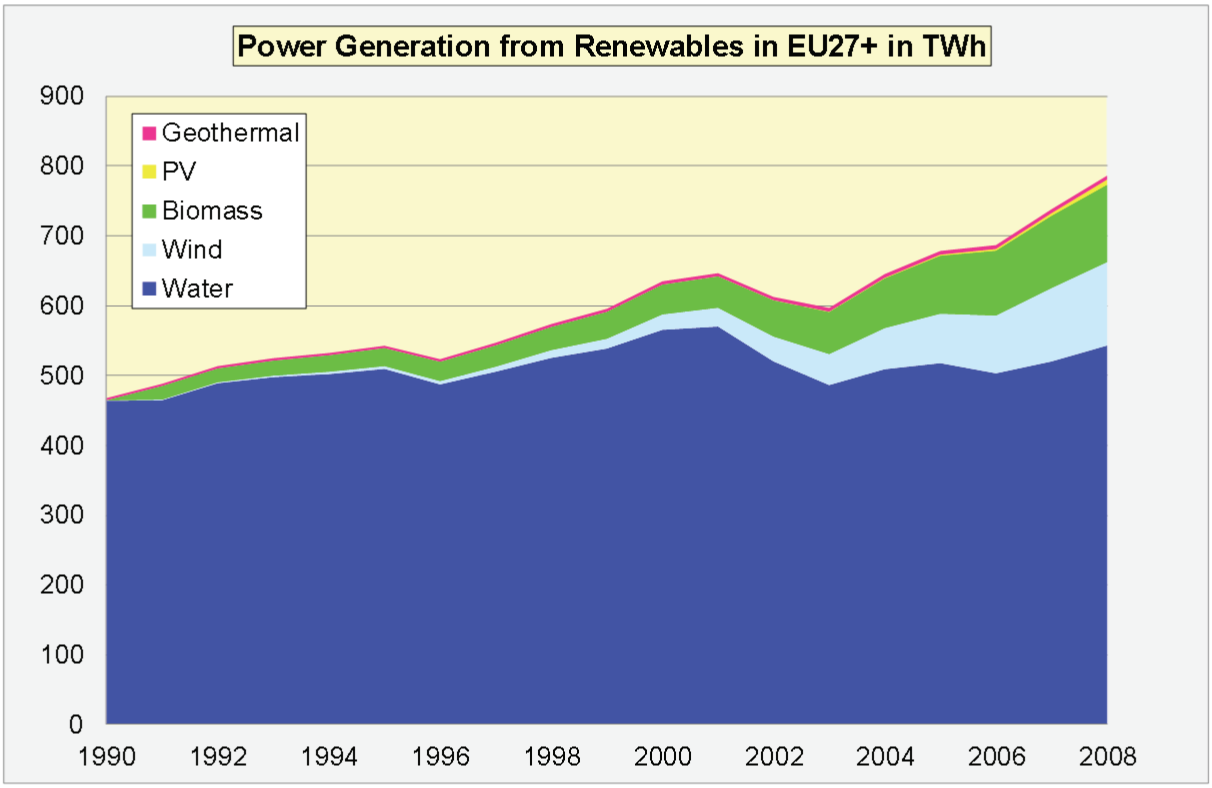

Figure 7: Development of renewables in EU27+ in TWh

2.3 Characteristics in some particular countries

As already mentioned the Top5 countries - with regard to their power generation – differ very much in the primary energy mix of their power supply. This has its origin in the national power strategy in the 60´s and 70´s as well as in the availability of natural resources in the country. Figures 8 and 9 give an overview on the power generation in 2008 as well as on the installed power capacities in Germany, France, UK, Italy and Spain.

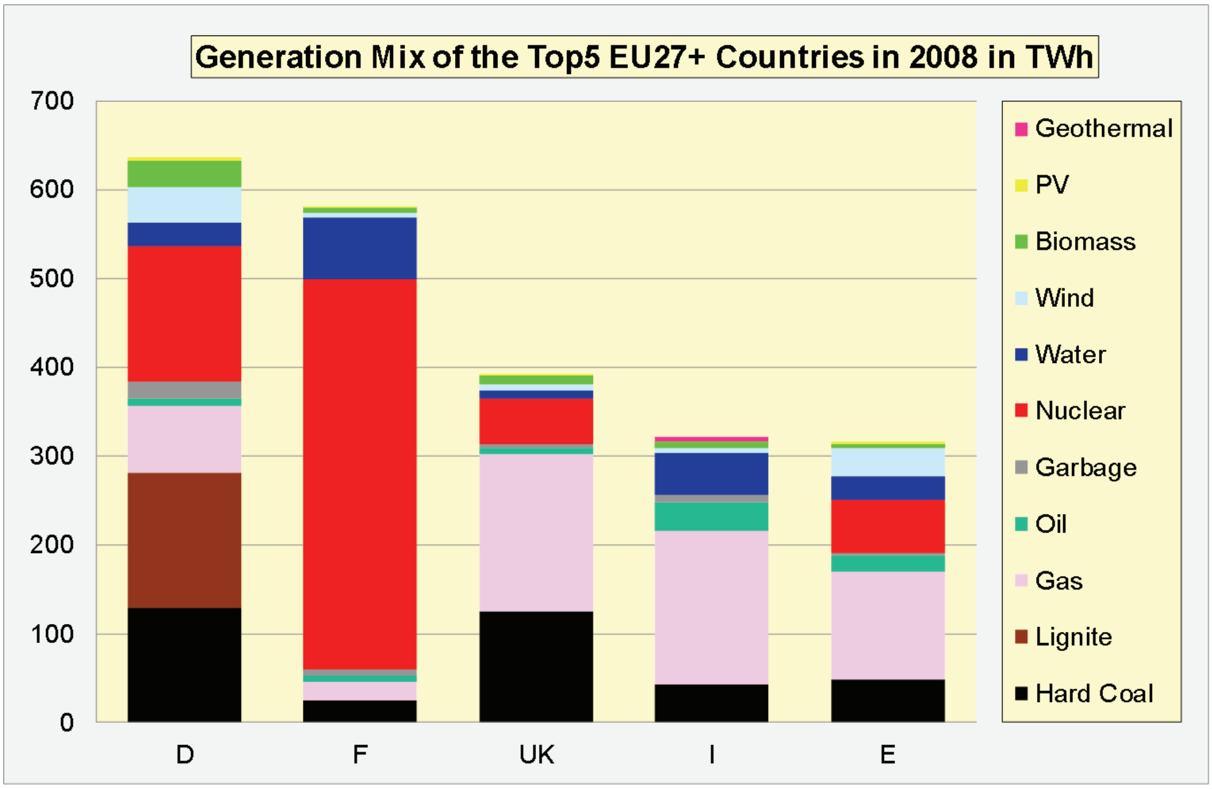

Figure 8: Power generation of the Top5 countries in TWh

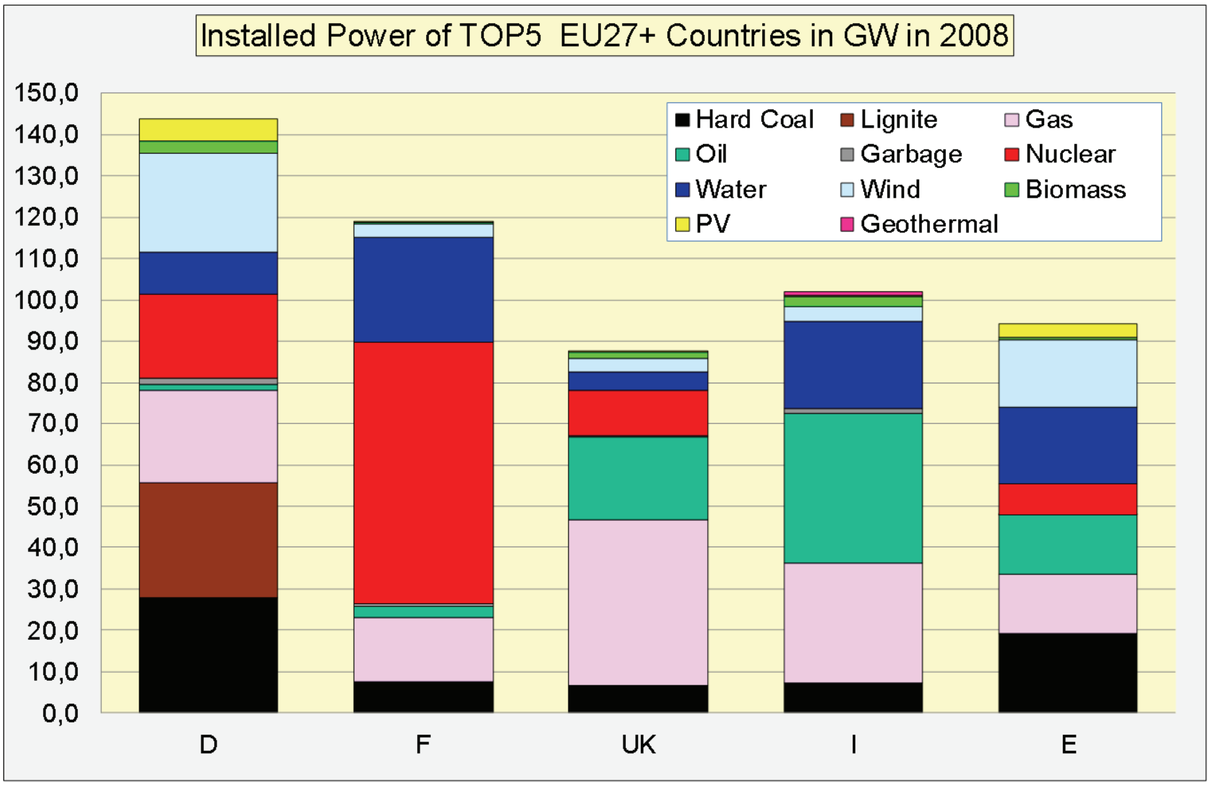

Figure 9: Installed power of the TOP5 countries in GW

In Germany the power supply was based historically on coal. In the 60´s the nuclear program initiated the development of nuclear power plants which resulted in the approximately 25% share of nuclear generated electricity at the end of the last decade. Gas fired power plants do also play a significant role in the German energy mix with the advantage of the excellent controllabilities. Today also renewable generated power contributes significantly to the German power supply with still very high growing rates. In 2011 the government has decided to step out of the nuclear program and to invest in renewables in order to reach a share of 80% in 2050 while reducing the CO2 emissions to 20% in 2050 compared to the 1990 level.

Very different is the situation in France. Here 80% of the power is generated by nuclear power stations and 15 % by water power plants. There is no significant contribution by coal, oil or gas power stations or renewables besides water. This monopoly situation probably will last for the next decades. A change would be a dramatic swing.

The generation mix of UK is very much determined by the natural resources of the country. Coal and gas play the significant role in generation with 45% respectively 32%. Nuclear contributes still 13%. The rest comes from water, wind and biomass. The large installed capacities in oil power plants resulted from the earlier use of UK´s own oil resources. They are not any more in operation today because of the swing to gas.

Italy has no fossil natural resources, only water in the mountain regions can significantly contribute to the power generation mix. Since it has decided not to operate nuclear power plants, it is strongly depended on import. Main primary energy resource is imported gas, by which 54% of the power is generated. Water contributes to the total by 14%, imported coal by 13% and oil by 10%. There was also in Italy a swing from oil to gas from 1990 to 2008. Italy is the only country in EU27+ with a significant generation by geothermal resources.

Besides Germany Spain is the only country of the TOP5 which has remarkable generation by renewable energies. Especially wind power turbines were invested in the last decade which generated 10% of the power supply mix in 2008. Main primary energy for the power supply in Spain is gas with 39% of the total. Coal and nuclear power plants are the other power generators with a share of 15% and 18 %. Although the country has a high potential in generating power by photovoltaic it had in 2008 no significant production of power by PV.

3. Changing role of electric power

3.1 State of the final energy and final electricity consumption

The main sectors of final energy consumption in EU-27 in 2008, according to figure 10 are in the areas of residential (24.6%), transport (32.6%) and industry (27.9%).

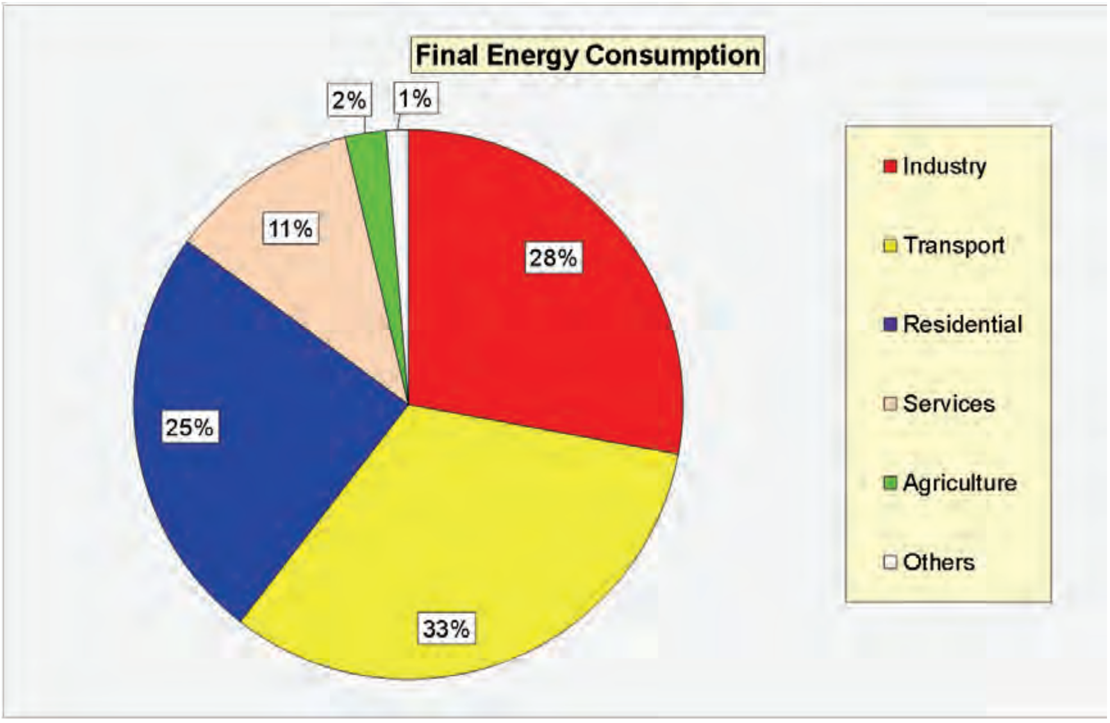

Figure 10: Main sectors of energy end-use in EU-27 in 2008 [3.1]

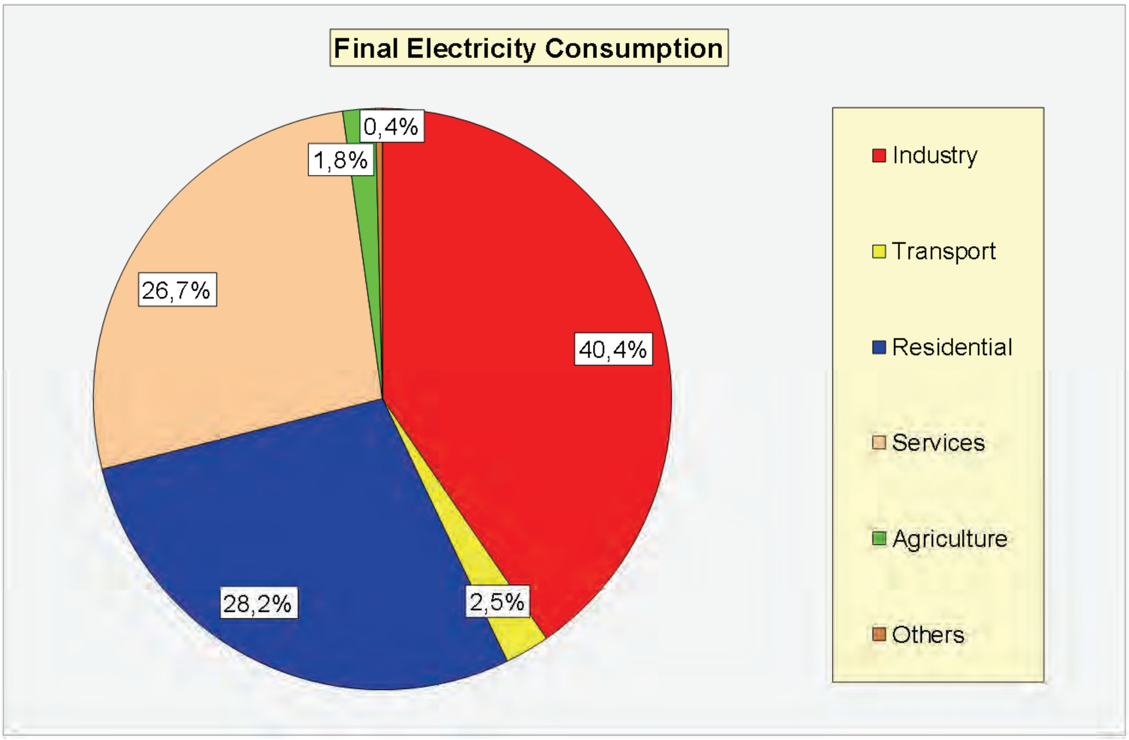

Figure 11: Sectors of final electricity consumption in EU-27 in 2008 [3.1]

Looking for electricity consumption in EU-27 the sectors of industry (40.4%), residential (28.2%) and service (26.7%) are dominant. The transport sector has only a share of 2.5% on electricity consumption but 32.6% on total energy. As will be shown later, the electrification of the transport sector to zero emission will be one of the main driving factors in saving fossil energy, improving efficiency in this sector and switching to renewable electricity.

In the residential sector the electricity has still a high portion of 28.2% of final consumption but also a high portion on primary energy of 24.6%. The total electricity demand of EU-27 represents 21% of the final energy end-use. Changing to renewable energy will be also being connected with changing from fossil to electrical energy. In the residential area a significant potential for saving of fossil energy is given the field of heating by thermal improvement of buildings and introduction of bivalent electrical heat pumps for heating and cooling.

3.2 Driving factors for switching from fossil to electric power

Urbanization of the world is in progress and is significant for electricity demand. In developing countries (D.C.) today about 45 % of the population is living in urban areas (Tab. 3-1), whereas in industrialized regions like in Europe still 75 % is reached. Urbanization is linked to electrification. In the EU 100% of the population is supplied with electricity. In D.C. in the urban areas the electrification rate is about 95 to 99 % and in the rural areas only about 60 to 70 %.

Table 1: Urbanization rate in per cent of total population in developing countries (D.C.) and industrialized countries (I.C.)

	1950	1960	1970	1980	1990	2000	2010	2020	2030	2040
D.C.	18.0	21.7	25.3	29.6	35.1	40.2	45.3	50.5	56.0	61.6
I.C.	52.5	58.7	64.6	68.8	71.2	73.1	75.0	77.5	80.6	83.5

Electricity represents clean energy and is the ideal form of supply for densely populated urban areas. The following factors for increasing electricity demand can be identified in the following sectors:

- End-use in the private sector: Here in future the demand will increase by Information and Communication Technology (ICT), air conditioning due to climate change, efficiency driven demand by home automation and electric mobility.
- Energy efficient buildings and smart cities: By thermal insulation of buildings the fossil energy demand for heating can be reduced in Europe by about 70 to 80 %. For building automation and air conditioning as well as heating by bivalent heat pump application the electricity demand will increase by about 10%, thus substituting fossil energy by electricity in a very efficient manner.

- Urban traffic: Urban traffic is mostly very environmental friendly in the urban areas. The urban public traffic is based on underground and tram, which is still fully electrical supplied. Urban bus fleets can be changed from combustion engines to battery electric power train and also taxi fleets can partly change to electric vehicle. But this will only increase the urban electricity demand by some percent.
- Suburban traffic: Around the centers of the mega cities of the future there are big areas, which are characterized by areas with low density population. In these areas the private electrical vehicle will have its main field of application and can increase the electricity demand here by up to 100 %.

3.3 Influence of renewable energy

Europe will change its generation scheme in the next decade toward at minimum 40% of renewable in energy end-use. Wind energy (Wind) and Photovoltaic (PV) will form the sources with the highest growing rates, while the classical fossil und nuclear power stations will keep their absolute value in installed power capacity, but will have lower time of usage which will shrink in some areas with high level of renewable energy sources (RES) to values below 2.000 h/a. Wind is linked to integration in the transmission grid, PV has mainly installations on the roof of buildings especially in rural and suburban areas and will be connected to the distribution grid. One problem in switching to renewable energy supply is that PV is synchronized by the sun radiation. There will periods in the distribution grid, where the generation exceeds the demand significantly. In future the grid philosophy must be to synchronize the demand to the generation by demand side management, e.g. with help of air conditioning or charging of car batteries. So increased electricity demand within a suburban area must not be linked to increased centralized generation.

3.4 Changing role of electricity in the transport sector

In the field of transport train, underground and tramway have changed in history to electricity. But the electricity demand of the sector of transport today has only a share of about 2%.

Electrification of the power train in car, bus and truck will show a tendency to electrification in the future for the following reasons:

- The electric power train has an efficiency of about 50% (plug to wheel) compared with only 15% for gasoline (tank to wheel) and 20% for diesel drives.
- Electric drives show zero emission and low noise and are thus ideal for cities.

- In urban stop-and-go traffic the electric drive can recuperate the retarding energy to the battery and has a superior performance compared to the combustion drive.

- Compared to the conventional car and truck there is a disadvantage in relation to rapid charging, which is very difficult to realize seen from the electric grid and from the power electronic for charging. So in the first instance the suburban and rural traffic will show electrification for short distance application and conventional low power charging.

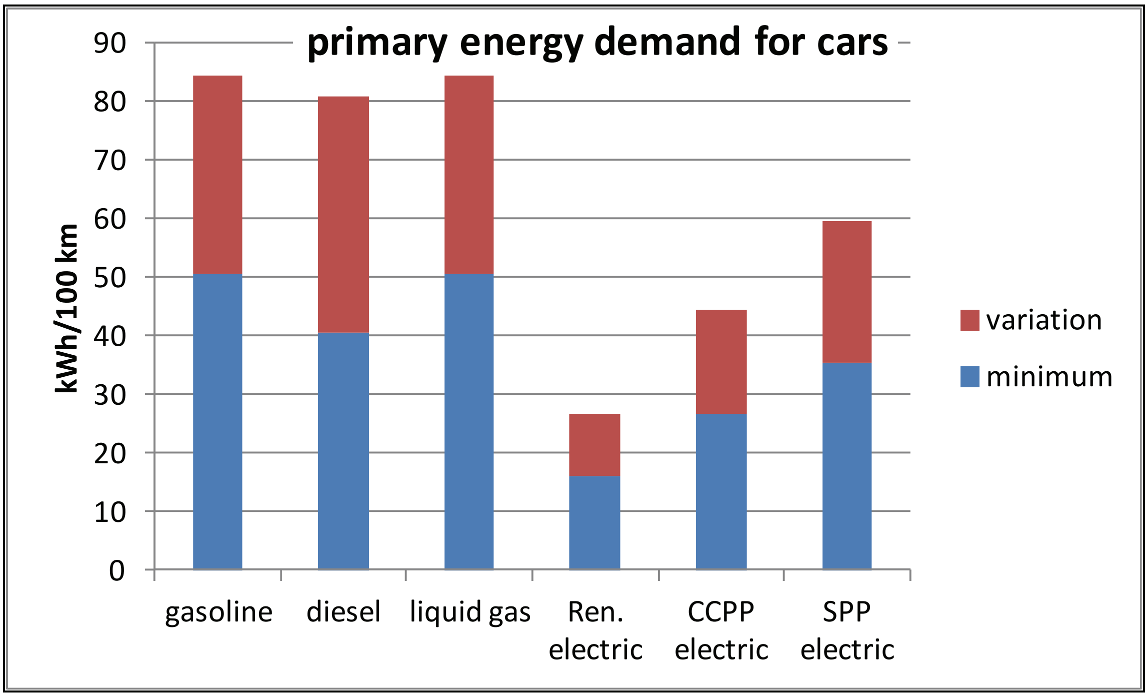

Figure 12: Specific energy demand of cars with combustion and electric drives

Figure 12 shows a comparison of different power trains in relation to their specific energy demand in kWh per 100 km and the typical variation range of different types. For the combustion drives the energy demand tank to wheel is valuated. For the electric drives supplied by renewable energy (Ren.electric), the efficiency plug to wheel is shown. For electricity from the grid the efficiency fuel to wheel is valuated, which includes the efficiency of the power stations (CCPP: combined cycle power plant with natural gas; SPP: steam power plant with coal), of the grid and the power electronic in the car for charging and discharging of the battery.

Electrification of the car brings a reduction of the energy demand plug-to-wheel to about 35% (Figure 12: Ren. electric) compared to fuel-to-wheel of the combustion car. If electricity is generated by a CCPP from natural gas and transported over a grid to the car and used for charging of the battery this needs only about half the energy compared to a car with a combustion engine and liquid gas. So electrification of the car even with electricity generated by natural gas or coal brings an efficiency improvement fuel to wheel.

The car battery can also be used as energy storage for renewable energy from PV or wind and so saving storage capacities in pumped storage hydro plants, which are limited. The electrification of all cars in Europe would need about 15% of the electricity demand of today but would save about 50% of the oil consumption.

Electrification thus increases efficiency, avoids emissions and allows renewable energy to be used for mobility.

Also seen from CO2-emissions electrification is very effective. In figure 13 the gray energy, needed for manufacturing, maintenance and recycling of renewable energy generators is valuated. For a mixture of 50% wind and PV about 15 to 25 g CO2/km is the content of the gray energy. Also electricity of CCPP is superior in emissions to direct use in a liquid gas drive. Only electricity from coal brings no advantage in emissions. In the long range the switching to predominant renewable electricity generation until 2050 will reduce the energy content from fossil power stations. But they will still be necessary for the stabilization of the power system at lower hours of usage.

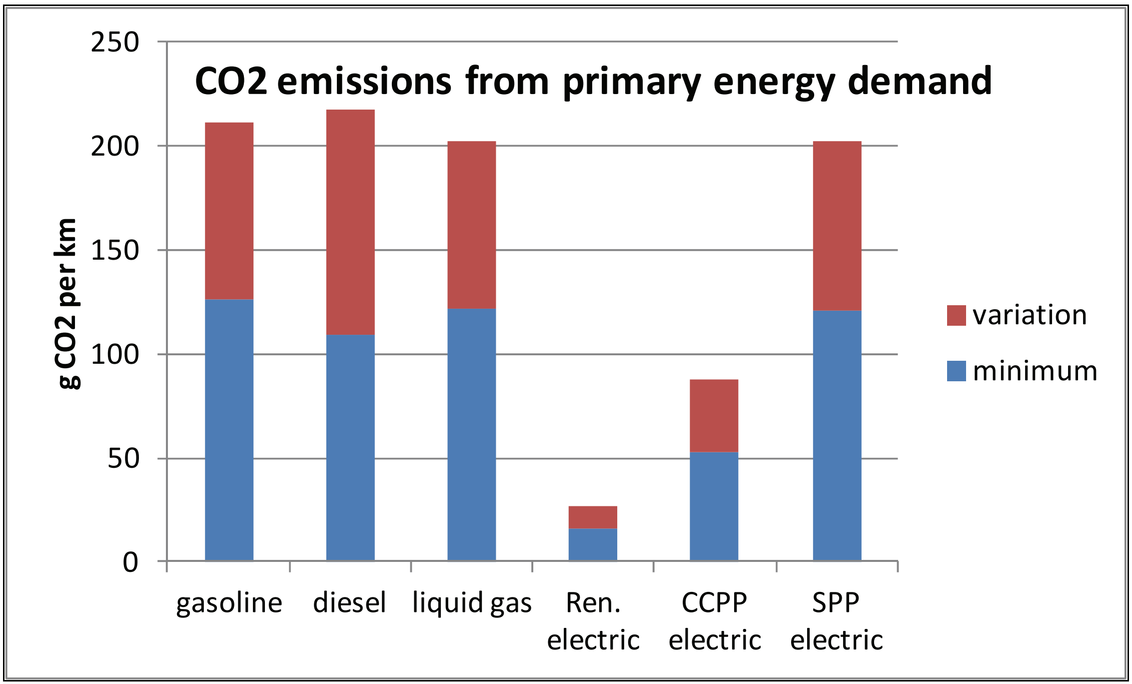

Figure 13: Specific CO2-emissions of power train concepts

Underground, regional train and electrical buses are most efficient in the urban areas and traffic will be probably related to these carriers. The electric car brings advantages especially in the suburban and rural areas. The fossil operated bus and the combustion car can be replaced by these efficient e-mobiles, bringing efficiency and zero emission. As the daily electricity demand for an e-mobile in the suburban area is about 5 kWh per day and two e-mobiles are needed per household, this will double the electricity demand of a household in the suburban area. Today it is difficult to predict the rate and speed of penetration of e-mobility in the suburban area.

The long distance traffic, will probably still be based on fossil fuel, as quick charging technologies show technological difficulties, especially seen from the electric grid. It seems that the hybrid electric drive operated with fossil fuel and electrical range extender, ecological hydrogen and fuel cell or with ecological methane and combustion engine will be the solution of the future.

3.5 Changing role of electricity in the residential sector

The “smart cities” initiative of the EU has the aim to bring efficiency in the private end-use sector. It comprises the energy demand of buildings, households, urban industry and commerce and of the urban and suburban traffic. Two targets have to be brought together in this context: improving efficiency in the end-use and renewable energy development. By these measures the fossil energy demand should be replaced by renewable energy under the condition, that the standard of living should not be significantly affected. Electricity will play a major role in substituting fossil energy by renewables and will increase its portion on the end-use energy demand.

For a household the following example is shown for changing of traditional to renewable and efficient end-use:

- Efficiency improvement of heating by thermal insulation of the building reducing the specific heating demand from 150 $kWh/m^2/a$ to 50 $kWh/m^2/a$ and using an electric heat pump instead of an oil-heating system will bring a further reduction to about 20$kWh/m^2/a$. Thermal insulation of buildings necessitates a ventilation system, with brings an additional electricity demand.
- Replacing old appliances by new and using efficient illumination brings a reduction in electricity demand by about 20 to 40%.
- Solar thermal water heating can save about 70% of electrical demand for this purpose.
- Replacing a car with combustion engine by an electric vehicle will reduce the energy demand of the car about 50 and replace gasoline or diesel by electricity.

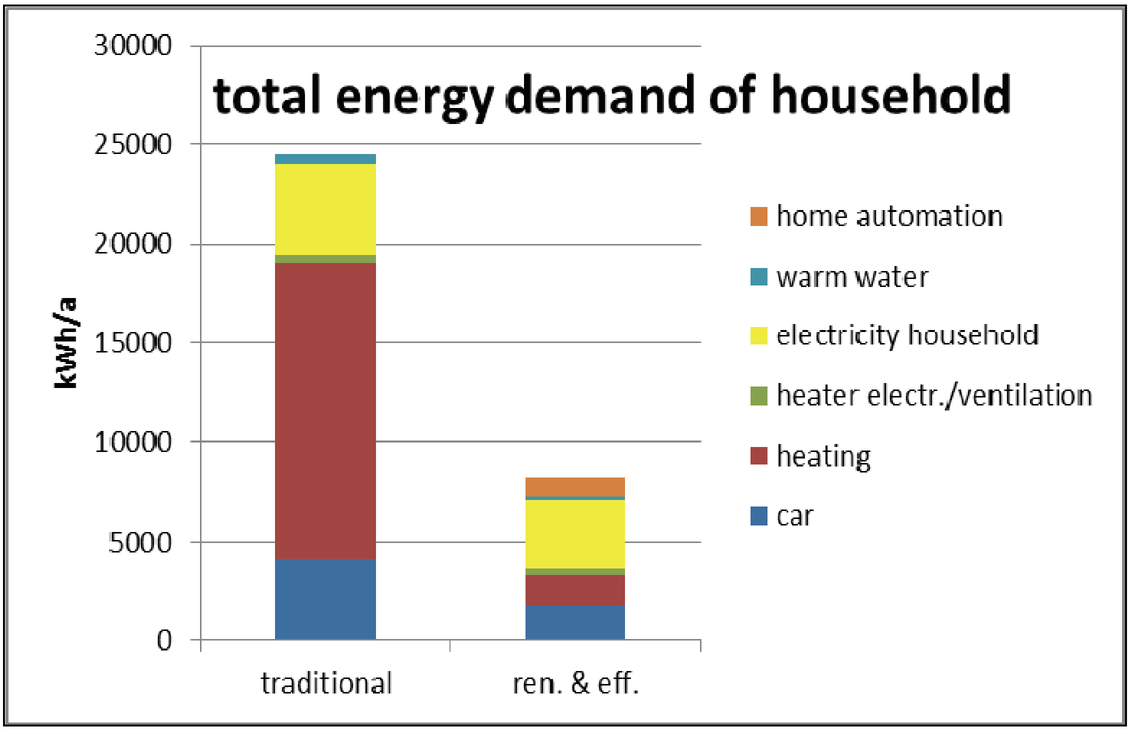

Figure 14: Reduction potential of total energy demand in the private sector (Traditional: standard home and car, ren. &eff.: renewable supply and efficient equipment)

In figure 14 the reduction potential of the total energy demand of a household is shown by new thermal insulated building, new appliances, efficient illumination and changing from fossil to electrical car. The annual energy demand can be reduced by these measures to about 35 %. In the traditional house the fossil energy had a share of 78% in the smart city environment theoretically it can shrink to zero. This is an ideal scenario. In reality still a backup system, consisting of grids, pumped storage capacities and fossil as well as hydro power stations is necessary.

The saving of fossil energy is connected with increased electricity demand, as shown in figure 15, which will increase to 150% by these measures. But in total this will save energy and reduce greenhouse gas emissions.

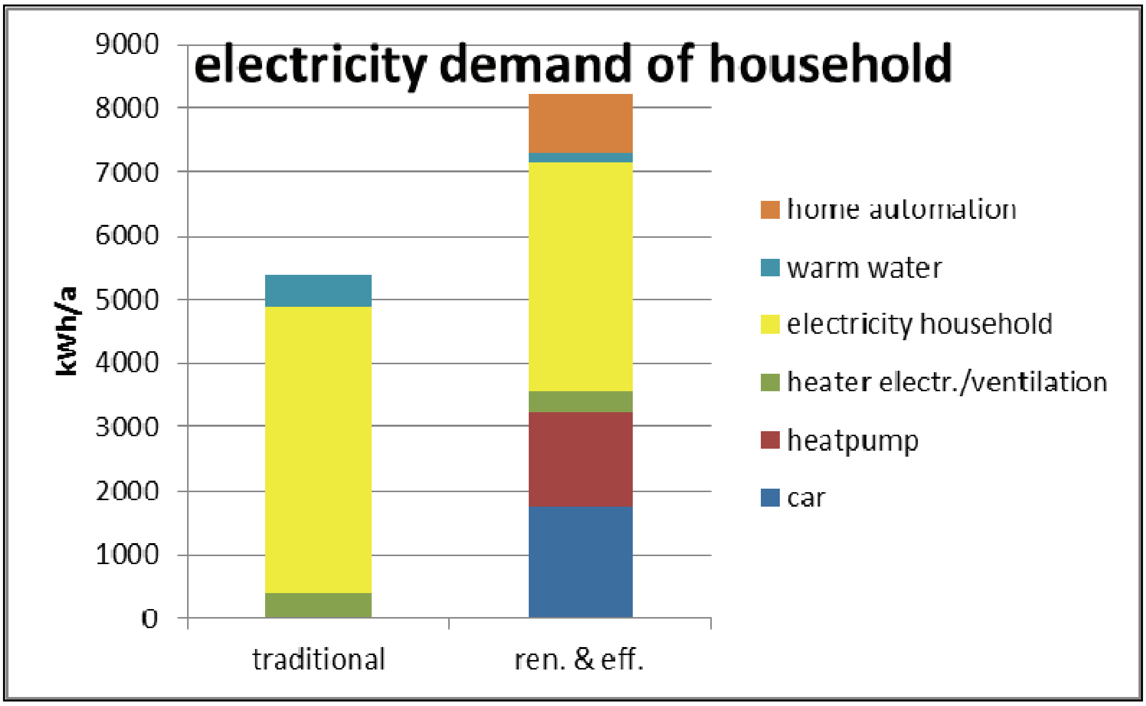

Figure 15: Changing electricity demand of households inclusive car

Additional electricity demand in the private sector comes from heat pumps, ventilation systems, home automation and electric car. The ventilation system will need about as much electrical energy as had been used in the fossil heating system for the water pump and the control and automation.

A large portion of this electricity demand can be generated regional by photovoltaic, wind energy and hydropower. Using photovoltaic about 80 m^2 of PV-collectors would be sufficient in Europe for a household, if a backup system exists.

This is a long term vision of the strategy of energy change. It necessitates the refurbishment of all buildings, replacing combustion cars by e-vehicles and exchanging home appliances by efficient ones. As insulated grid operation is not reliable and uneconomic, also the extension of the superposed power transmission and distribution grid, of the storage capacities and the installation of flexible power generation is necessary.

3.6 Future role of security of supply

Electricity from wind and PV represents fluctuating generation systems and need grid extension, storage capacities and more flexible consumers and backup power stations. Electrical mobility and energy-active cities and regions will in future represent flexible consumers. Especially electrical mobility in the suburban and urban areas is characterized by short distances per day mostly in the range below 50 km. So a flexible charging according to the renewable energy situation from wind and PV will be possible. Also in the private sector to some extend Demand Side Management (DSM), especially in the field of heating and cooling will be possible and can help to reduce the investments in backup supply installations like power stations and large storage capacities.

Seen from industry and security relevant energy infrastructure the potentials of DSM are limited. Especially the manufacturing Industry is highly automated and much dependent on interconnected in-time logistic systems. Here a secure and predictable electricity supply is also in future vital important. In the sector of primary industry, especially in the steel industry the melting furnaces can to some extend be flexible for shorter time periods. Also the energy infrastructure for railway and local transport, energy supply of buildings and offices needs as secure and reliable electricity supply.

Security of supply is linked to an energy backup system, consisting of transmission and distribution grid, energy storage capacities and flexible backup power stations.

So in parallel to the renewable energy sources (RES) the traditional centralized electricity has to be reinforced and adapted for the integration of the RES and maintaining security of supply by flexible thermal and hydraulic power stations to enable system control.

4. Environmental, economic and political requirements on the supply security of electrical power.

The following statements summarize the results of the policies of the European Union and the deliberations of the European Parliament until 2012 and take on considerations of national governments. They are not results of this study.

4.1 Green-house gas (GHG) reduction goals

Well aware of the finite nature of primary energy such as coal, oil, gas and uranium and having regard to the impact of recent energy conversion processes on the environment and climate change, the international community has been trying to establish sustainable development and global justice for the world population since 1992 at the "Conference on Environment and Development" in Rio de Janeiro and the follow-up conferences. The climate conference in Kyoto in 1997 has decided for the first time internationally binding targets for the reduction of greenhouse gasses like carbon dioxide, methane, nitrous oxide, hydro fluorocarbons and sulfur hexafluoride until 2012 by 5.2% compared to 1990. In 2010 the last World Climate Conference in Cancun agreed only to continue the implementation of the Kyoto - agreements without setting new targets for the period after 2012. However, all parties recognized the so-called "2-degree target" for the first time, to limit the global warming to 2 ° C.

The European Union and its 27 Member States have helped to shape the world conferences and actively committed, not just to meet the objectives agreed but to achieve them earlier with all the options of an advanced industrial society and even to exceed the goals qualitatively and quantitatively. Some EU member states see themselves in an even greater responsibility to the future generations and participate in the implementation of UN programs and EU decisions by even more ambitious goals.

The EU has committed itself in 2007 under the target triple of “supply, competitiveness, environment", to reduce the CO2 emissions by 2020 by at least 20% compared to 1990. But this would not be sufficient to limit the heating of the atmosphere at 2 ° C. Therefore, the bodies of the EU consider increasing the reduction target to 30% by 2020. By 2040, emissions are to be reduced by 60%. With the use of “low-CO2” technologies no CO2 should be emitted any more in the power generation industry by 2050. However under the assumption that the share of renewable energy will rise to 55%, nuclear energy will continue to be used and carbon capture and storage of CO2 (CCS) will take place. To achieve those targets the EU "climate package” with the trade of emission rights can help. It is binding for all Member States as of 2013

The use of fuels containing hydrocarbon during the past 200 years made the current development of industry, commerce, mobility, prosperity and well-being possible. But the foreseen shortages of supplies and the growing pollution generated by the conversion of the fuels give us only 40 years of correction.

With the "Declaration on the Future Energy Supply" of September 2011, the World Engineers Convention (WEC) together with national engineering associations stepped into the discussion of the international community on the search for an ecological, economic and socially sustainable energy future. Reducing the emissions will increase productivity, will save resources and will make energy affordable.

4.2 Implication of Liberalization

The supply of primary energy and electricity is the most important task of the internal market in the EU. This task includes the guarantee and the extension of the supply security and a non-discriminatory market access as well as socially acceptable electricity tariffs.

The implementation of the energy and environmental goals of the EU and the implementation programs of individual member states require the extension and renovation of power plants and networks. The usable potential of renewable energies in the EU countries exceeds the expected electricity demand in total despite all the differences in the individual countries. The different agricultural potentials and the fluctuations of “natural” fuels demand the expansion of storages and networks as the most important measure. For the transmission of power between the national grids the coupling points must be enforced in order to use the different feed-in potentials and to fulfill the actual load demand. The ongoing modification and expansion as well as the forthcoming renewal of the power plant fleet must be used to a broader use of renewable energies.

With the increasing use of renewable energies the renovation from the previous conventional large power plants to quickly reacting new power plants should be used to fulfill the new network requirements. Further, a structural change of the grid is a necessary requirement for a non-discriminatory electricity market as a key part of the European single market.

The increasing diversity of power infeeds in conjunction with a closely meshed network structure is a requirement for cross-border electricity trade to equalize the Europe wide supply and demand.

4.3 Electricity price policy and price control

The cross-border trade in electricity volumes will increasingly take place with the necessary expansion of the internal energy market increasingly. Therefore an EU-wide legal framework is needed to ensure transparency in price formation, to provide guidance for necessary investments in energy production systems and networks and to prevent market abuse. This requires that the energy regulatory authorities in the Member States cooperate with the "EU Agency for the Cooperation of Energy Regulators (ACER)." The collection of data should be done only nationally, but with the mandatory transfer to the EU agency.

The “Regulation on Energy Market Integrity and Transparency (REMIT)” and the “Directive on the taxation of energy products and electricity “ which are in the process of the parliamentary discussion should be pursued. The market surveillance rules for electricity are to be adjusted to the rules of the EU emissions trading law. Power should be valued on the basis of the energy content and not on the basis of the CO2 content. This energy content-based taxation is to encourage more efficient energy use and energy savings.

In the Federal Republic of Germany the work of the Federal Network Agency has proven of value. EU regulations to organize socially acceptable energy prices, to promote economic growth and employment and to provide clean and renewable energies should be measured should be compared with those of the Federal Agency.

With the conversion of the energy system from a central, load-optimized power supply structure to a decentralized, load-and-supply-side structure with an intelligent power management the municipalities will transform with their abilities from an energy consumer to also energy supplier. The municipalities will take over an important task for informing and instructing the citizens to improve their consumption behavior. In this context the creation of the "Covenant of Mayors in the EU" with the mission of promoting EU environmental and energy targets deserves great importance.

4.4 Dependency reduction from suppliers of primary energy from outside the EU 27

The conversion of the centralized power generation structures with the consumption of mostly imported primary energy like coal, oil, gas and uranium to more decentralized renewable power plant systems opens the chance of reducing the import dependence from fossil energy sources. Today we spend per year € 290 billion or about 3% of the GDP of the EU member states for the import of oil, gas and coal. In Germany two recently published concepts for a future carbon-free energy supply with the title "Sustainable Energy System 2050," from the German renewable research network and "Towards 100% renewable power" from the Advisory Council on the Environment come to the conclusion that in Europe the potential of renewable energy resources is much higher than the demand for energy. However these statements assume that all EU measures are implemented consequently and in time to restructure the energy supply system. These measures are:

- Power generation from renewable energies
- Extension of the grid and control of both the supply and the demand through intelligent network management,
- Significant improvement of the efficiency in electricity generation and power consumption,
- Development of combined heat and power plants.

The EU and all member States with external borders should use all options to support their neighboring countries to reconstruct their own electricity markets, analogous to the goals and programs of the EU. This support should focus on collaboration of science and research and technology transfer. Emphasis should also be put on energy policy cooperation between the Mediterranean countries and North Africa for the use of solar energy, as well as collaborations with Scandinavia for the use of water resources for energy storage. HVDC - technology must be implemented for the transport of electricity keeping in mind that power is versatile in application and easy to transport. Because of its broad applicability power will also become a “primary energy” for the storage of hydrogen or methane and for electric drives of the individual and public mobility.

4.5 Efficiency improvement to reduce costs and to protect resources

Increasing energy efficiency is clearly the most cost-effective part of the energy revolution. According a DENEFF study investments in energy efficiency measures amortize in less than nine years. According to calculations by the EU Commission (COM 2008/772), an average household can save 1000 € per year by energy efficiency measures. Overall, in the EU the possible energy savings by energy efficiency measures and in the energy conversion process of coal, oil, gas and uranium to electricity and heat are twice as much as the energy generation potential of renewables.

The EU “Directive on the Energy Performance of Buildings" from May 2010 provides the guidelines for the reduction of 40% of the total energy consumption in the EU. This is also true for the power consumption. The aim of the Directive is a “Low-Energy-Building” with a very high energy performance. The energy for those buildings should come from renewable resources.

The nationally to be defined methods for the calculation of the total energy performance and its monitoring should be supervised by the EU using national facilities. Sections of the calculation of the total energy efficiency are controlled by the EU "Directive on Information and Labeling of the Energy Consumption of Products." since May 2010. For information about the energy consumption of a device beyond this directive all products which have impact on the energy consumption but do not consume energy by themselves should be labeled.

On June 22, 2011, the European Commission published a proposal for a "Directive on Energy Efficiency”. To achieve the 20% saving goal of the EU until 2020, a mix of measures are proposed:

- Energy saving obligations for energy producers, for example by supporting investments of customers with annual energy savings of 1.5%.
- More information of customers about their energy usage through monthly bills with the presentation of comparable data for the previous year and the average consumption.
- Commitment of the public sector to bring 3% of their buildings to minimum energy standards.
- Promotion of the energy service sector e.g. with energy-contracting by third parties.
- Removal of barriers in the tenancy law for efficiency investments.
- Promotion of combined cycle power plants wherever appropriate.

The regional and temporary fluctuation of power generation by renewable power plants will increase with renewable energy mix. To balance these fluctuations with the demand for electricity so-called smart grids are required. In order to control the power consumption of the end-user more effectively, but also to optimize their personal need and to control the utilization of the grid more effectively intelligent measuring and monitoring systems coupled with intelligent information and communication systems between providers and consumers are required. National regulatory incentives for grid operators and energy producers to build and operate such intelligent networks should be based on achievable efficiency gains and cost savings.

Based on the “European Technology Platform Smart Grids” which was founded by the EU guidelines for the development and operation of such grids should be provided, research contracts for the necessary technology and standardization as well as the regional development of smart grids are to be coordinated.

The reorganization of the energy supply, particularly of electricity supply, with the expansion of decentralized structures, calls for new materials and products using so-called rare earth. Already today solar and wind energy conversion equipment as well as communication and mobility technologies are heavily dependent on rare-earths.

As with other finite energy sources such as coal, oil, gas and uranium we are dealing already today with the shortage of these "rare" metals. The mining of those metals is coupled with the environmental pollution and significant energy consumption.

Together with the restructuring of our energy supply system and our behavior on energy and material consumption we have to ensure the recycling of these valuable resources after the end of the products´ life cycle. The material recycling has to be proven already with the production of the goods.

5. European electrical power demand in the next decades

5.1 Development of power demand from 1990 to 2008

The power demand in the various member states of the European Union is a mirror of the industrial, residential and services development state of each country. Electrical power substitutes more and more other forms of energy since the electrical current shows high flexibility in its different forms of application, can easily be transmitted and controlled and is environmental clean, seen from end-use and renewable generation . These attributes are the reason that the demand of power has continuously risen in the last decades. The growth of power demand is still the case in the EU27+ although in some countries the growth of primary energy use is already stagnating.

Figure 16 shows the development of the power demand in EU27+ from 1990 till 2008 (Note: all data are from EUROSTAT). It is structured in the sectors industry, transportation (only electrical trains!), residential, services and agriculture. The agriculture sector is compared to the others very small and will not be considered anymore in the following.

The overall growth was 1,6 % per annum over the whole period. The demand was 2290 TWh in 1990 and rose to 3042 TWh in 2008. The industry consumption grew by 0,8 % per annum. It had a share of 46% in 1990 and decreased to 40% in 2008. While the power demand in the residential sector increased with an average growth rate of 1,8 %, the services sector ramped up by 3,2 % per annum from 465 TWh to 880 TWh. These changes reflect on one hand the switch in the industry sector from heavy power industry to more high tech industry with less power demand and on the other hand the high investment of the industry sector in energy efficiency measures. Parallel to this industrial shift the services began to boom in the late 90´s with a growing demand in power.

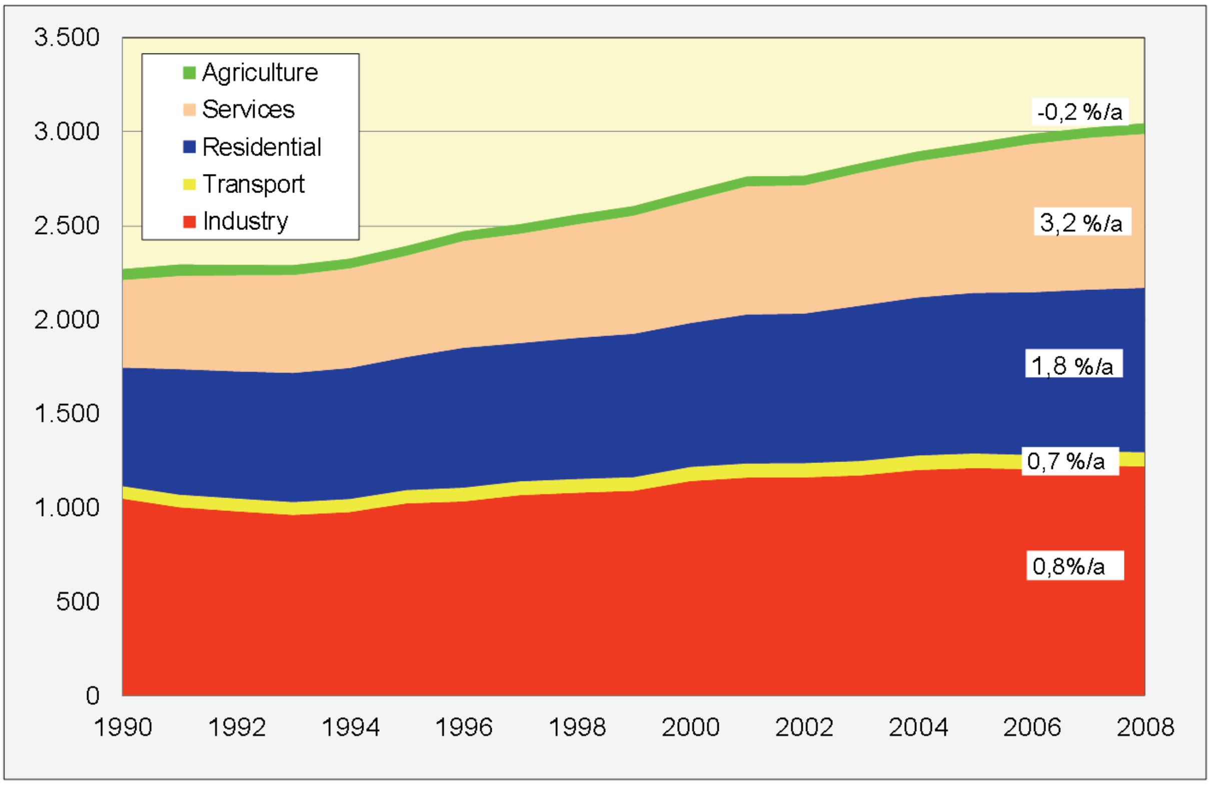

Figure 16: Power consumption in EU27+ in TWh

This phenomenon can principally also been observed in the Top5 countries in EU27+, but with individually different growing rates (figure 16). While in Germany and UK the power demand rose only 1,2 % per annum in the observed period the increase in France and Italy was 2,1 %. Spain boomed by a plus of 4,2 % per annum.

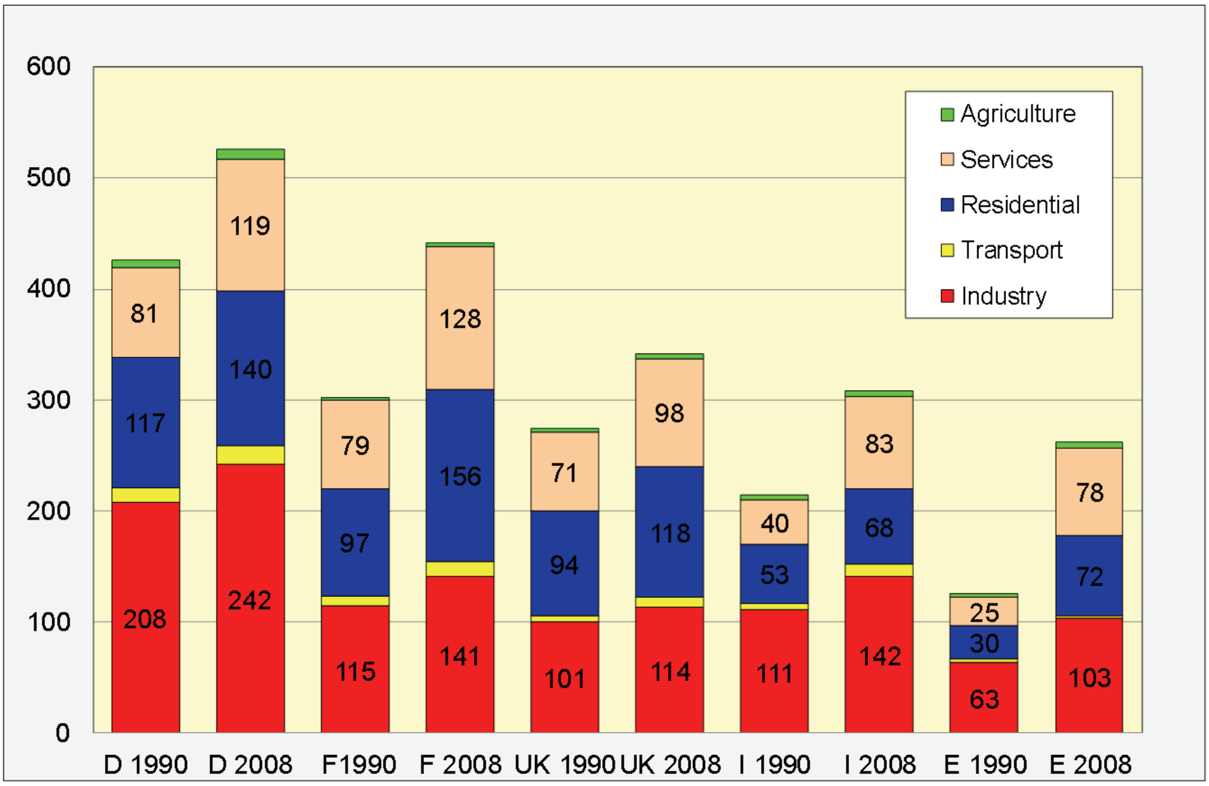

Figure 17: Power demand in the EU27+ top5 countries in 1990 and 2008 in TWh

It is notable that while the power consumption share of the industry in Germany and Italy is on a 45% level, it shows in France and UK only a 33% share. The Spanish industry demands 39 % of the total power consumption of the country. In the residential sectors the situation is vice versa: The French and English households have a high demand with a 35% share, while in Germany, Italy and Spain this number is 27 %, 22 % resp. 27 %.

5.2 Estimation of the power demand until 2050

The model for the estimation of the power demand in the future, i.e. until 2050, is based on a combination of a top down and a bottom up model. In any case the demand is individually estimated for industry, transportation, residential, services and agriculture.

5.2.1 Method of estimation

The estimation is calculated by four basic components (figure 17): firstly the past development of the demand is observed and put forward to the future trend. The past five years play in this context the important role. By this procedure the current trend is incorporated into the model. Secondly the efficiency potential of the different sectors is estimated and taken into account in the future development of the power demand. Thirdly new applications powered by electricity are identified and incorporated into the estimation model. These new applications will increase the power demand and counterbalance the efficiency improvement effects. The most important of those new applications are heat pumps, air-conditioning, ventilation (needed for strongly isolated houses), e-cars and e-light trucks. All of the new applications will influence the power consumption in industry, households and services, only partially in transportation and agriculture.

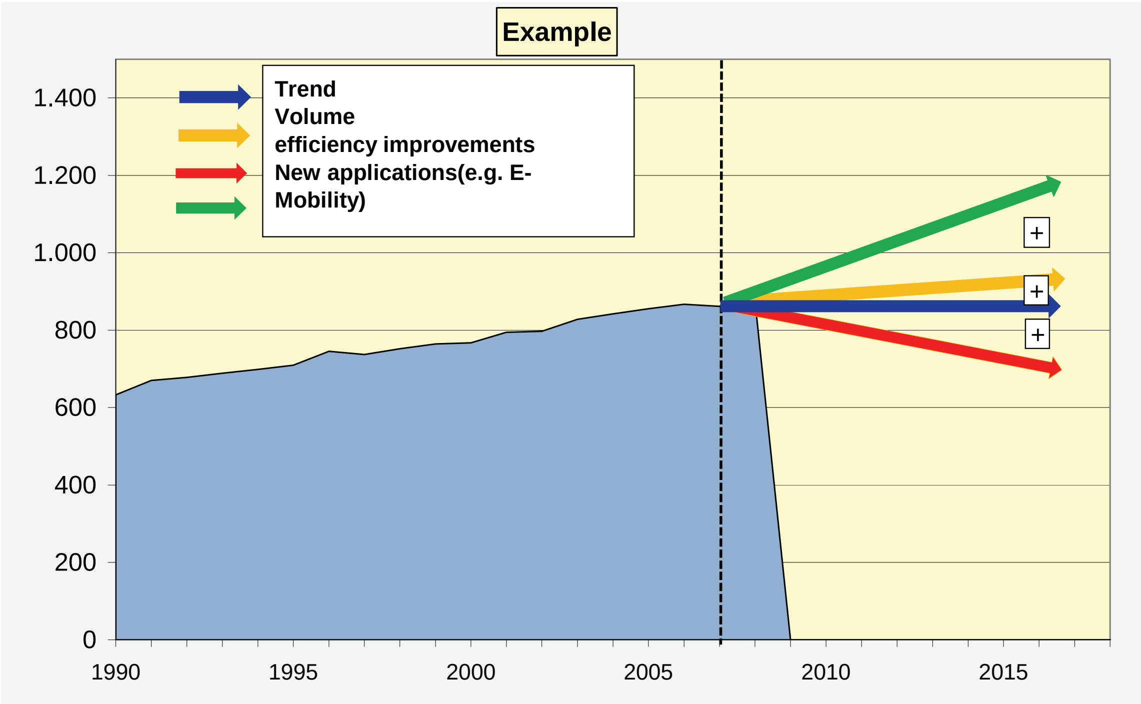

Figure 18: Methods of estimation

Finally, an important factor for estimating the future demand is the demographic factor (=volume factor). On one hand the number of the EU27+ inhabitants will decrease by 5 to 10% until 2050. On the other hand the number of households will rise and thus the number of used devices (e.g. refrigerators) and so the power demand. Both factors are included in the estimation model.

Besides those 4 basic components of the estimation model the forecast is split into two scenarios: a conservative and a progressive scenario. The conservative approach considers an efficiency improvement of 0,5% per annum in industry and transportation and 1% in the residential and services sector, while the progressive approach is based on 1% yearly efficiency improvement in industry and transport and 1,5% in the other two sectors. With regard to new applications the conservative scenario foresees a slow introduction of new applications. The progressive approach take into account, that these new application will come into use on a much higher speed. An example: in the conservative model it is assumed that in 2050 30% of all cars are e-cars and of all light trucks only 10% are e-trucks. The progressive approach considers that in 2050 there will be 50% e-cars and 30% light e-trucks. These assumptions are the best with our today´s knowledge. They are of course discussable and there may be total other opinions how the e-mobility will develop. Still estimation is better than none.

Using this four component model the estimation of the future power consumption seems to be relative complete. Still all estimations for the future especially for such a long period are based only on our knowledge today and may be obsolete when tremendous unforeseen changes happen.

5.2.2 Estimation in the various application areas

- - Industry sector

Permanent investments in energy efficiency improvement to lower the productions cost will show a continuous reduction of the power demand for the industry. This effect will be stronger in the progressive scenario resulting in a stepper decline as seen in figure 5-4. The power demand in industry was in 2008 1219 TWh and will decline until 2050 to 1120 TWh in the conservative scenario. In the progressive scenario it will go down to 830 TWh. The reason for such a massive reduction of power demand results from the estimated 1% per annum efficiency improvement in the future. In the conservative scenario the efficiency rate was estimated to 0,5 %

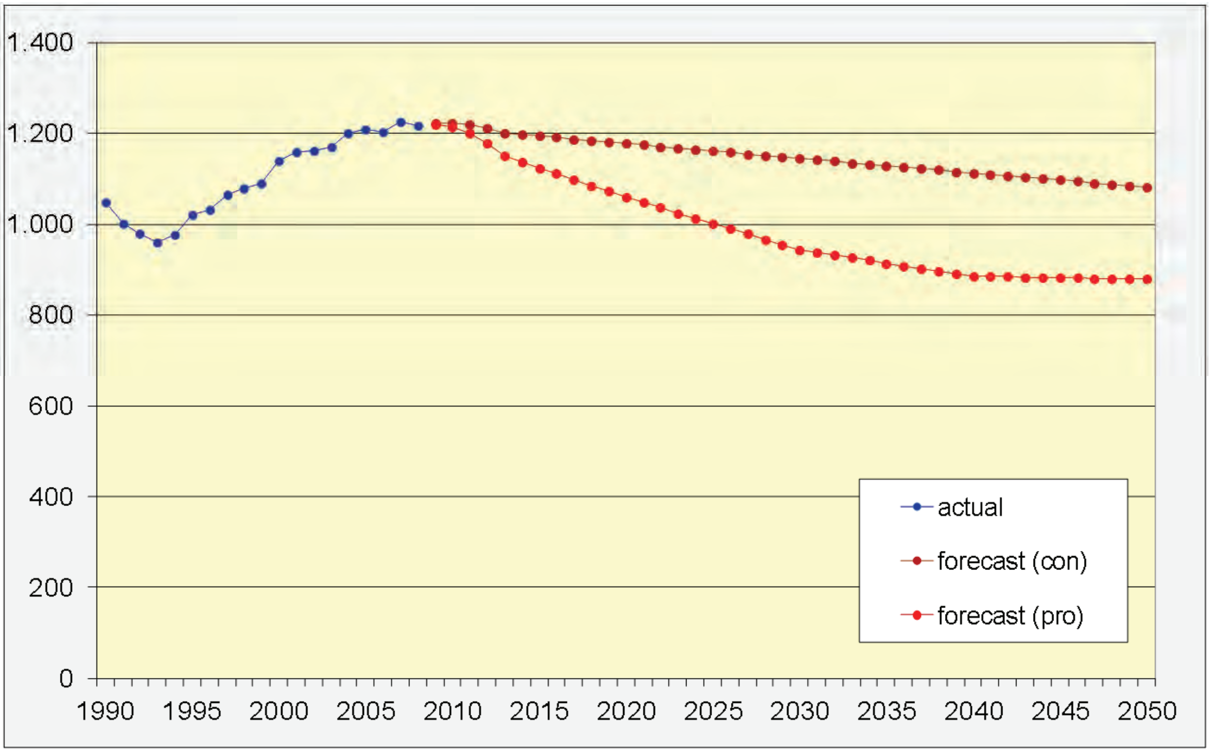

Figure 19: Industry power consumption in TWh

- - Transportation sector

The transportation sector follows in principle the industry trend (figure 20). But the decline in power demand is steeper than in the industry sector. The new applications described above will have no influence on the power demand. Only the electrical drives of the trains demand mainly the power in the transportation sector. Further, the magnitude of power consumption in this sector is more than a factor 15 smaller than in the industry sector.

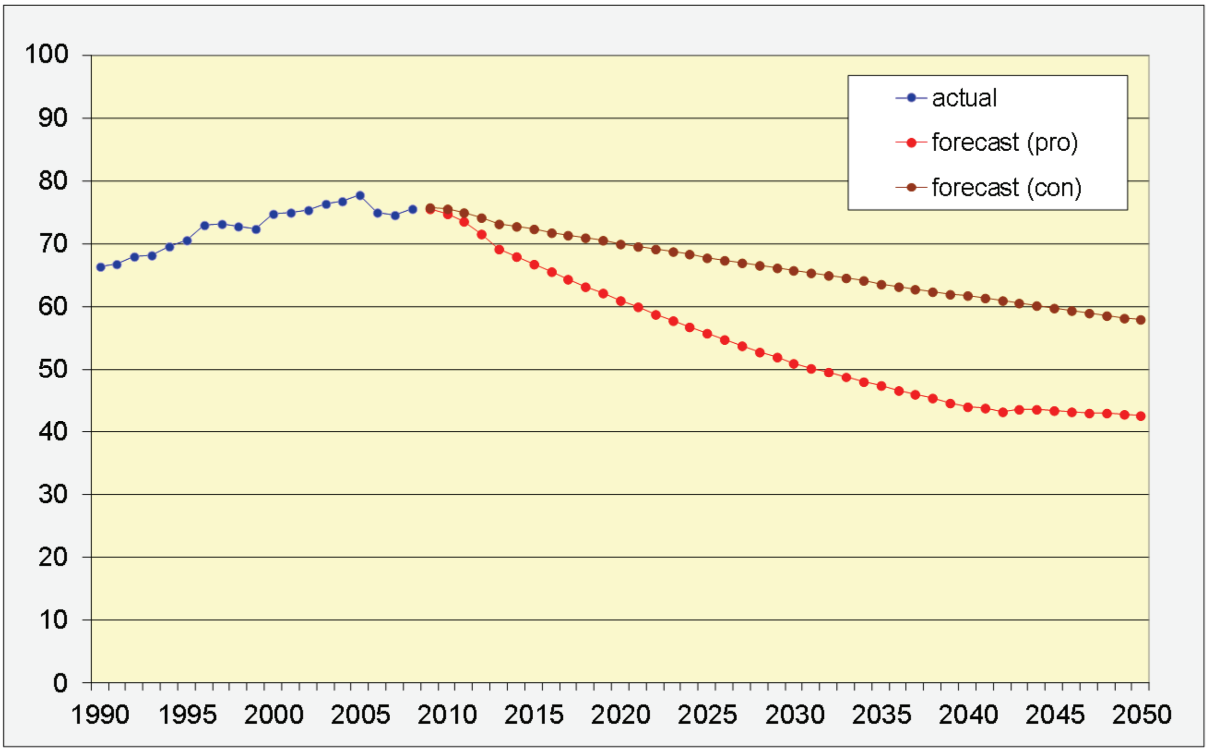

Figure 20: Transport power consumption in TWh.

- \- Residential sector

The increase of power consumption in the residential sector will move on (figure 21). Although we see in this sector efficiency improvement of 1,0 % in the conservative scenario and 1,5% (!) in the progressive the new applications for heating and climate in the households as well as the e-cars will have a dominant influence. From 876 TWh in 2008 the demand will rise to 1350 TWh respectively 1700 TWh. More households and the use of electricity instead of fossil energies will result in a doubling of the consumption.

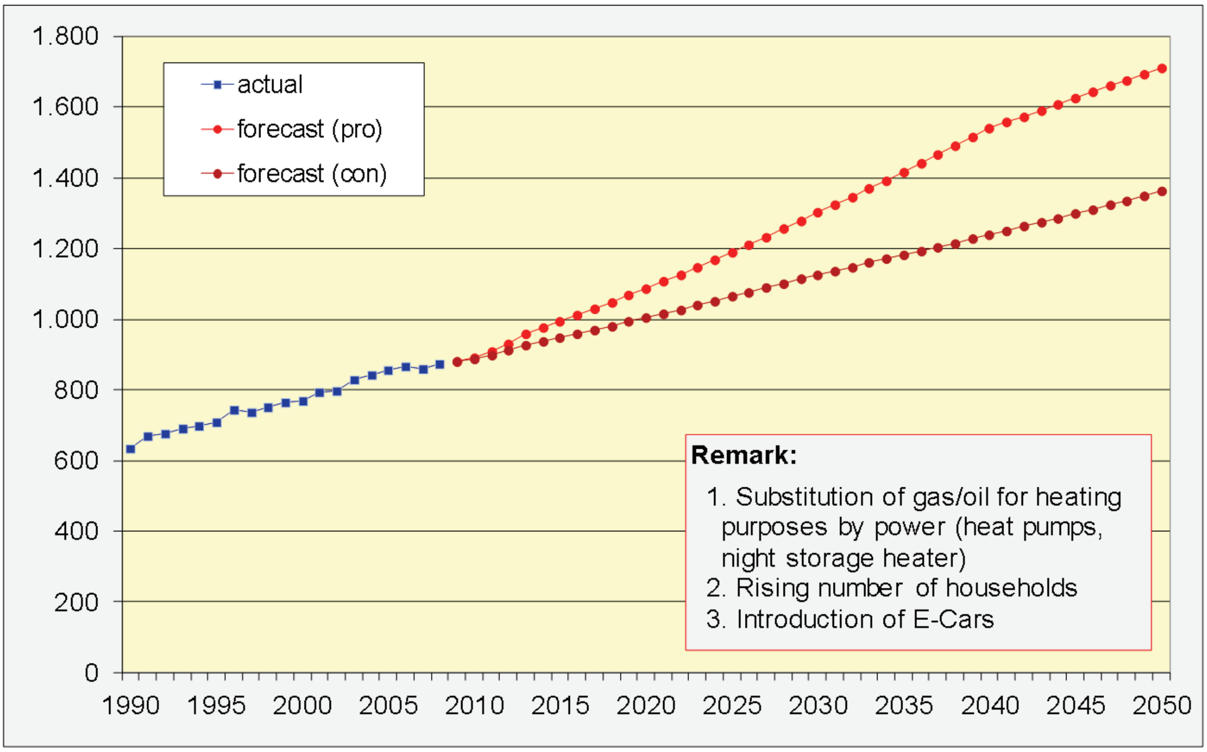

Figure 21: Residential power consumption in TWh

- - Services sector

The services sector shows the same behaviour as the residential sector (figure 22). Also here the new applications dominate the efficiency improvement. The power demand will rise to 1450 TWh in the conservative scenario and 1350TWh in the progressive scenario until 2050.

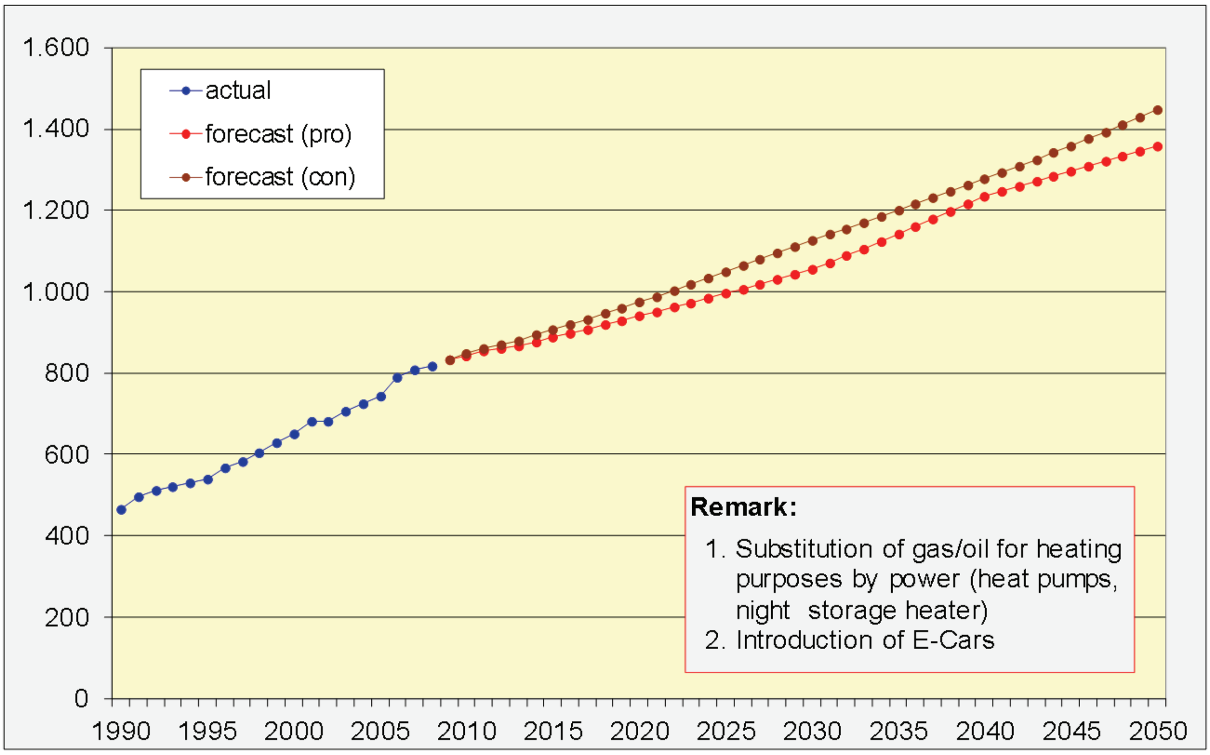

Figure 22: Services power consumption in TWh

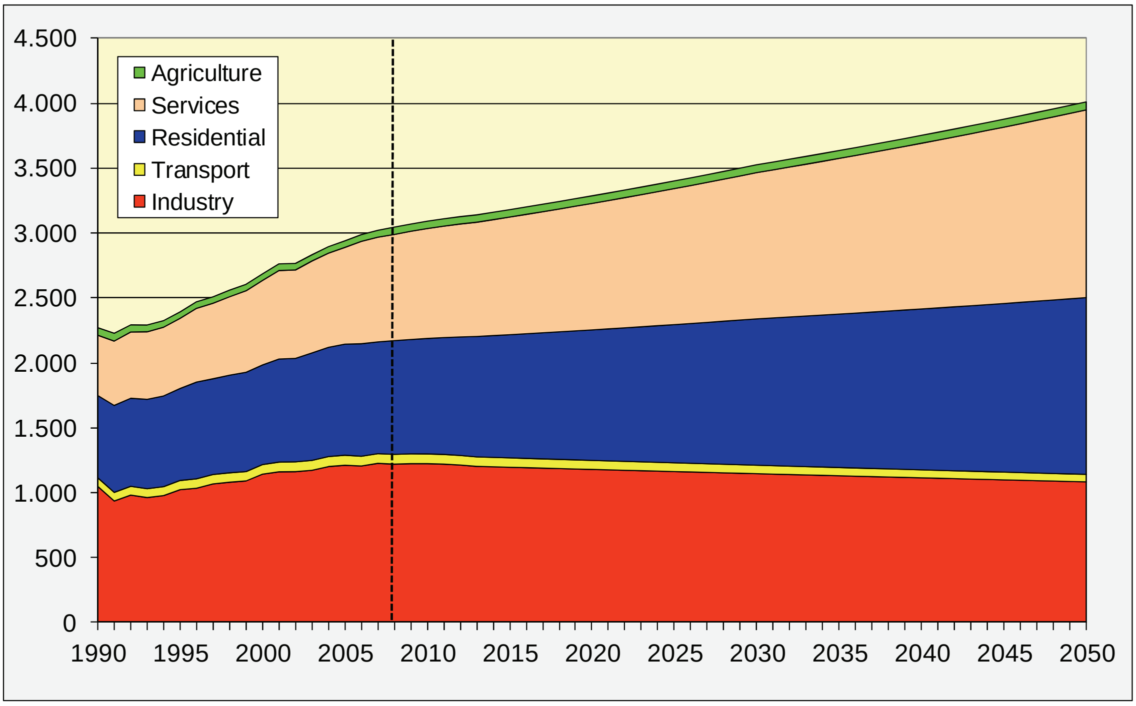

Figure 23: Overall power consumption in TWh in EU27+ (conservative scenario)

Figure 23 displays the overall power consumption in EU27+ until 2050 for the conservative scenario while figure 24 shows the demand in the progressive approach. These figures are the sum of the four discussed sectors plus the agriculture sector which is not displayed since it is very small compared to the others..

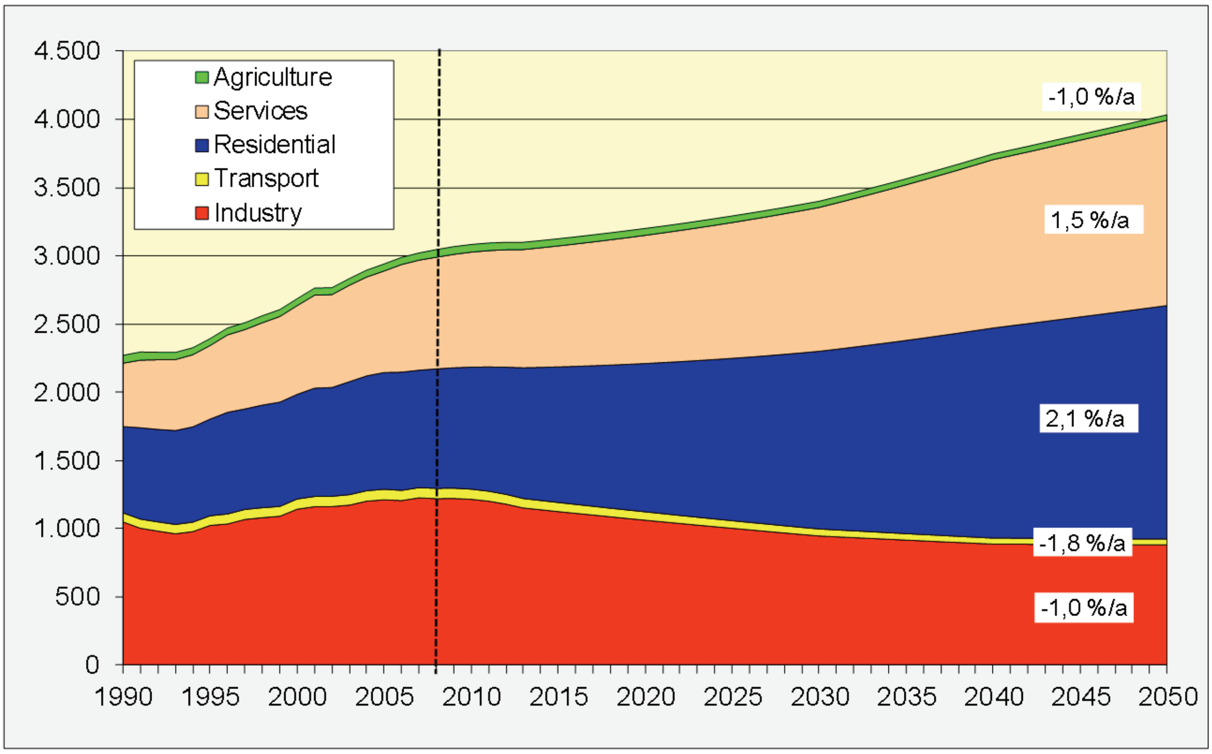

Figure 24: Power consumption in TWh in EU27+ (progressive approach)

The power consumption in 2008 was in the EU27+ 3043 TWh. On the basis of the above described estimation model the demand will rise until 2050 to approximately 4050 TWh. This is an increase of 1,2 % per annum. This is slightly higher than in the last 3 years with 1,1 %, but much less than the increase of 1,7 % since 1990. The moderate number for the last 3 years is the result of energy efficiency measures in the various countries in EU27+ while the high number since 1990 is an expression for the growth of the European industry as a whole. One might presume that the growth rates will further decrease because of further investment in energy efficiency measures. But this will be not the case because of the new power applications in the coming years. This is in line with a general trend from fossil energy driven applications to electricity driven applications.

6. Options for future bulk power transport and supply security of power

6.1 Introduction

Typically, the value creation chain in electricity markets comprises three constituents: the production side (generation of electricity), the demand side ("consumption" of electricity) interlinked by transmission and distribution grids. The latter play a crucial role as they "transport" electrical energy from the power plants to the customer. The transmission system operates with high voltage levels over long distances, similar to a system of motorways or highways. From the transmission level the power "flows" into the sub-transmission grid and eventually into the distribution grid comparable with a system of local roads. Transmission and distribution of electrical energy can be seen as different functions having different technical characteristics, i.e. in terms of voltage level, grid topology and used assets. This chapter only deals with the transmission system targeting questions of bulk power transport, i.e. the transmission of "massive amounts" of electricity. First, a brief overview is given how the transmission system in Europe evolved. In a second step current and future challenges for the transmission system are described, including the integration of high-shares of fluctuating infeeds from renewables, the creation of the internal European electricity market together with related questions in terms of cross-border congestion management. The chapter is concluded with prospective economic and technological options in order to ensure the secure functioning of transmission grids in Europe.

6.2 The Transmission Grid in Europe – Current Situation and Challenges

6.2.1 Historic Evolution of the UCTE / ENTSO-E Grid

The existing power grid in Europe is a highly-interconnected system, spanning the whole of Continental Europe with connections to neighboring systems e.g. in Scandinavia (Nordel), the United Kingdom and Russia. The current structure of this meshed, supra-national system was largely influenced by available generation technologies. Conventional thermal power plants and hydropower plants have been characterized in economic terms by significant economies of scale, i.e. the larger the plant, the more cost-efficient is electricity generation. Hence, it was reasonable to build plants with a rating of several hundreds of Megawatts and then to transport electricity over long distances to the load centers (i.e. cities). In the 1950's efforts started to couple the different national networks to a supra-national system of networks. This was achieved through the foundation of the UCTE. In 1958 the transmission grids of Switzerland, France and Germany were coupled. During the following decades other national networks joined the UCTE. In 2008 the UCTE was replaced by its successor organization ENTSO-E with 41 members. Technically this means that all transmission systems of the member countries are operated together as one so-called synchronous zone. The objectives of creating such a “compound” system were (among others) to benefit from the possibilities to help each other in emergency situations, to provide back-up power and to exchange “excess” power. To fulfill these functions the cross-border interconnections between the countries gained more and more importance. However, individual countries operated to a great extend as autarkic zones, i.e. generation capacities were in most situations sufficient to cover domestic demand. This resulted in limited cross-border exchanges.

6.2.2 Transmission Challenges Driven by Electricity Trade

For optimal coordination of power plant and network expansion as well as operational requirements, it appeared natural that one vertically integrated company would serve all elements of the value creation chain. Through this integrated view utilities were able to optimize the operation, maintenance and reinforcement of the whole system. This structure persisted until the early 1990s, when the power supply industries worldwide started to undergo extensive changes. Electricity markets moved away from vertically integrated monopolies towards liberalized structures. The value creation chain was unbundled with generation, transmission and distribution being separated services, no longer offered by one large utility but by several distinct providers.

The national liberalization processes were supported by legislation from the European Union targeting the creation of a single European electricity market. In regulation 1228/2003 it is stated that “The creation of a real internal electricity market should be promoted through an intensification of trade in electricity, which is currently underdeveloped compared with other sectors of the economy. “ Generally, the liberalization efforts led to a significant increase of cross-border trading activities, and in turn, to an increase of cross-border power flows. As the interconnectors usually served purposes in terms of handling emergency situations and sharing system services with only very limited power exchanges strong cross-border congestions can be observed nowadays. Interconnectors are more often driven to their thermal and stability limits. Challenges are also posed by fluctuating flows induced by very short-term (intra-day) trading activities. Potential remedies include transmission investments, i.e. the reinforcement of congested corridors as well as the further development and implementation of so-called efficient congestion management schemes like market coupling. These options are described in the corresponding sections below.

6.2.3 Transmission Challenges Driven by the Production Side

In the period between the 1950s until the 1980s investments into large “conventional” thermal or hydro power plants were prevailing. However, the introduction of the Combined Cycle Gas Turbine (CCGT) provided a technological justification for competition. The CCGT technology allowed for smaller plant sizes, being at least as economical as conventional thermal and hydro plants with their large economies of scale. This trend was continued by advances in technologies concerning electricity production by means of wind turbines, photovoltaic and solar thermal facilities. Electricity infeed from these technologies is fluctuating due to geographically and temporally changing weather conditions. Fluctuations can only be predicted with a limited accuracy. As in power systems supply and demand always have to be balanced, appropriate measures must be deployed in order to react to variations on the generation as well as on the load side. In case of imbalances, primary frequency control stops any frequency change in the system due to a mismatch of generation and demand. This automatic control stabilizes the grid frequency to a small band of deviation. Secondary frequency control is activated to bring the grid frequency back to its nominal value (50 Hz in Europe). Finally, tertiary reserves are used to relieve primary and secondary control reserves and to guarantee that new disturbances in the system can be faced. Primary, secondary and tertiary controls are standard concepts in system operation since decades. However, the change of the production mix towards higher shares of infeed from fluctuating renewable sources leads also to an increased demand for reserve power.

Another challenge for the transmission system is the change in the spatial distribution of generation facilities. Investments into off-shore and on-shore wind farms lead to substantial infeeds away from the traditional load centres. Thus, power has to be transported over longer distances from e.g. off-shore sites to the coast and then further inland. Additionally, the so-called DESERTEC initiative foresees the building of solar-thermal power plants in North Africa. If this plan materialises, the new generation areas have to be connected to the existing grids in Africa and Europe. It is also likely that additional investments are to be made in order to reinforce the existing system and adopt to the changing power flow patterns in the network. Technological options are described in the corresponding section below.

6.2.4 Transmission Challenges Driven by Demand Side and Developments in the Distribution Grid

Climate change, fossil resource depletion, policy incentives as well as higher public awareness in term of sustainability have promoted the deployment of small decentralized and renewable generation technologies, typically including photovoltaics, micro turbines, combined heat and power (CHP) etc. Together with the implementation of distributed storage technologies or the prospective integration of Plug-In Hybrid Electric Vehicles (PHEVs) complex interactions in distribution systems arise. The traditional “setup”' of the power system with the typical power flow from higher to lower voltage levels may be altered. Infeeds from lower voltage levels are becoming increasingly common. Additional developments on the demand side concern the transformation of formerly “passive” consumers to loads, which can be integrated actively by means of demand side participation. In doing so, loads (consumers) in conjunction with storage devices and small renewable generation units may contribute to traditional concepts, like secondary control etc. Such developments are likely to influence also higher network levels. There may be a trade-off between supra-national investments or regional or local “solutions”, i.e. by investing into micro-grids.

6.2.5 Conclusion

The above section gave a short introduction to the historical evolution of the UCTE / ENTSO-E grid. A number of prevailing challenges for the transmission system, and thus for bulk power transport have been identified. The following sections try to identify market-based and technological solutions to respond to the identified challenges and to ensure the reliable operation of the power system in the long-run.

6.3 Market Options for the Facilitation of Future Bulk Power Transport

6.3.1 Cross-border Trading and Market Coupling

It is expected that large scale integration of renewable sources puts congestions on power balancing mechanisms even in large systems. For the efficient integration of renewable sources (e.g. wind and solar generation), new market structures are required. One of the new approaches is to combine the different national market places in order to use trading and balancing procedures across borders. This has been proposed by policy makers and regulators. With so-called market coupling the daily cross-border transmission capacity between the various areas is not explicitly auctioned among the market participants, but is implicitly made available via energy auctions on the power exchanges on either side of the border (hence the term implicit auction).

Spot markets of different countries are already merged. Currently, Germany, Belgium, France, Luxembourg and the Netherlands share their day-ahead markets 0. Even control areas outside the Central West European system are coupled to this market. For example, the NorNed cable (HVDC) connects the Dutch grid with the Norwegian grid. Furthermore, the integration of more renewable generation demands trading closer to real-time operation. This ensures keeping positions balanced between the day-ahead stage and real time operation. In addition, the intra-day spot market coupling would be a further step towards market integration. Belgium and the Netherlands are the first countries already performing such an intra-day coupling.

6.3.2 Cross-border balancing

Another step forward is the coupling of balancing markets for real-time operation to deploy balancing resources (secondary reserves) from other control areas. When a certain control area monitors an area control error (ACE), balancing services could be deployed from TSOs across the border. The first step towards cross border balancing is the share of ACEs among participating control areas. If a certain area is long (more export as scheduled) and a certain area is short (more import as scheduled), both TSOs will not deploy balancing services but share their opposite imbalance. In general ACE-netting decreases the total amount of requested balancing services. Since the beginning of 2012, the four TSOs of Germany, together with TSOs from Denmark, the Netherlands and Switzerland apply ACE-netting 0. Besides this type of balancing services via market coupling, there are other market designs to balance across the border, defined by ETSO and EER (European Energy Regulators). The ultimate objective is to implement one common merit order list for the entire Central West European system to deploy the most cost-efficient balancing services.

Nevertheless, these new types of cross border deployment of energy and capacity will affect system operation and power transmission. Frequency deviations due to cross border trading are already noticeable on hourly transitions 0. In addition, the future will reveal if cross-border activities will touch congestion areas. It has to be taken into consideration that cross border trading and balancing must not violate the N-1 criterion at any time.

6.4 Technological Options for the Facilitation of Future Bulk Power Transport

When it comes to network investments different technological choices exist that depend on the specific project. Generally, a cross-border interconnector can be regarded as a coupling between two neighbouring grids. The network parameters and the method of operation of either system influence to a large extend the final investment decision. Most networks around the world are based on alternating current (AC). Thus, if there are no specific reasons of technical or economic nature, these networks will be coupled AC synchronously.

In some cases, synchronous coupling is impossible or economically not desirable, namely:

- with coupling between systems with different nominal frequency or a different mode of frequency and voltage regulation;
- with long cable connections, as in the case of sea crossings (distances greater than 30-40 km) due to the capacitive effect of AC cables;
- with a weak coupling between two grids because of stability problems.

In these cases, instead of using AC, energy may be transmitted by high voltage direct current (HVDC) using an overhead line, an underground or submarine cable, or a combination of these [6-1]. Converter stations to switch between alternating and direct currents are needed at both ends of an HVDC connection. Distinction can be made in true DC connections and the so-called back-to-back installations (see Figure 25).

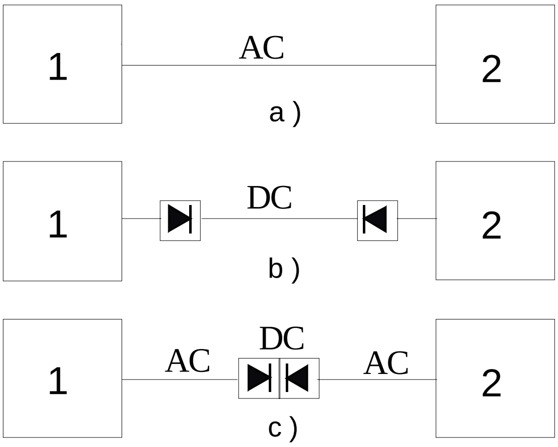

Figure 25: Connection of systems

In the case of synchronous connection also the choice of the voltage level of the links is relevant. Nowadays, 380 kV in Europe and 550 kV in North America is the predominantly applied highest voltage level, but there may be a need for a higher voltage level in the future as studies show. Voltage levels of 750 kV, 1000 kV and 1200 kV are conceivable. In North and South America 765 kV lines are already present. As in Eastern Europe a 750 kV line was built, it is possible that this trend continues there, and perhaps spreads also towards Western Europe. In Russia from the Urals to Kazakhstan an 1150 kV line is in service. Also on other places around the world there are experiments with voltages higher than 1000 kV. The main reason for using a higher voltage is the ability to increase the transmission capacities, and in turn, decrease network losses, which is important for transport over longer distances.

Figure 26 shows what a higher voltage means for the tower image. The DC solution is also drawn. The capacity of the 750 kV line is twice that of the 380 kV line, the DC line has the same capacity as the 750 kV line, but can be built in the same trace width as the 380 kV line.

For AC coupling, the line costs are dominant to the substation cost. At DC, the substation costs (converters) are higher than at AC, but the cost of an overhead DC line is lower than that of an AC line. So there is a break-even point where the total costs are equal to each other. With the current cost ratios, the distance over which DC is cheaper is about 500 km; with (land) cable connections it is about 50 km.

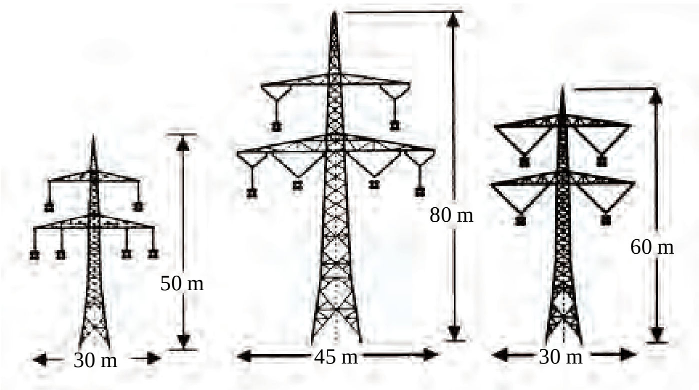

Figure 26: Tower images of AC and DC lines

Alternating current cables (AC cables) are most often used in densely populated areas such as large cities or under water. The cost of manufacturing and installing such cables is higher than the corresponding costs of overhead lines for a given length. The most serious limitation for the use of AC cables is the fact that they cannot be used for long connections without extra devices, compensation reactors, which are needed at intervals along the cable to limit the reductions in transmission capacity arising from the reactive currents in AC cables.

The transmission capacity of an AC cable is rather limited compared with overhead lines. It is constrained by heating of the cables and is strongly restricted by the length of the connection. The major disadvantages of AC cables are therefore their high costs and short length. Their main advantage compared with overhead AC lines is the reduced visual impact. HVDC cables are not limited in length.

6.5 Case Study

The following case study is intended to give an indication of how network investments will influence total generation costs in Europe. The results were computed for a scenario in 2050 with high-infeed from renewable sources, such as wind and photovoltaics. Generally, network congestion leads to higher generation costs as cheap generation units are constrained-off by the bottlenecks in the transmission system. Congestion relief will lead to lower generation costs as generation can be utilized more efficiently. Figure 27 shows the annual average of line loading in the base case situation (without network investments). Red lines indicate congestion. The generation costs for such a scenario amount to 61 billion Euros.

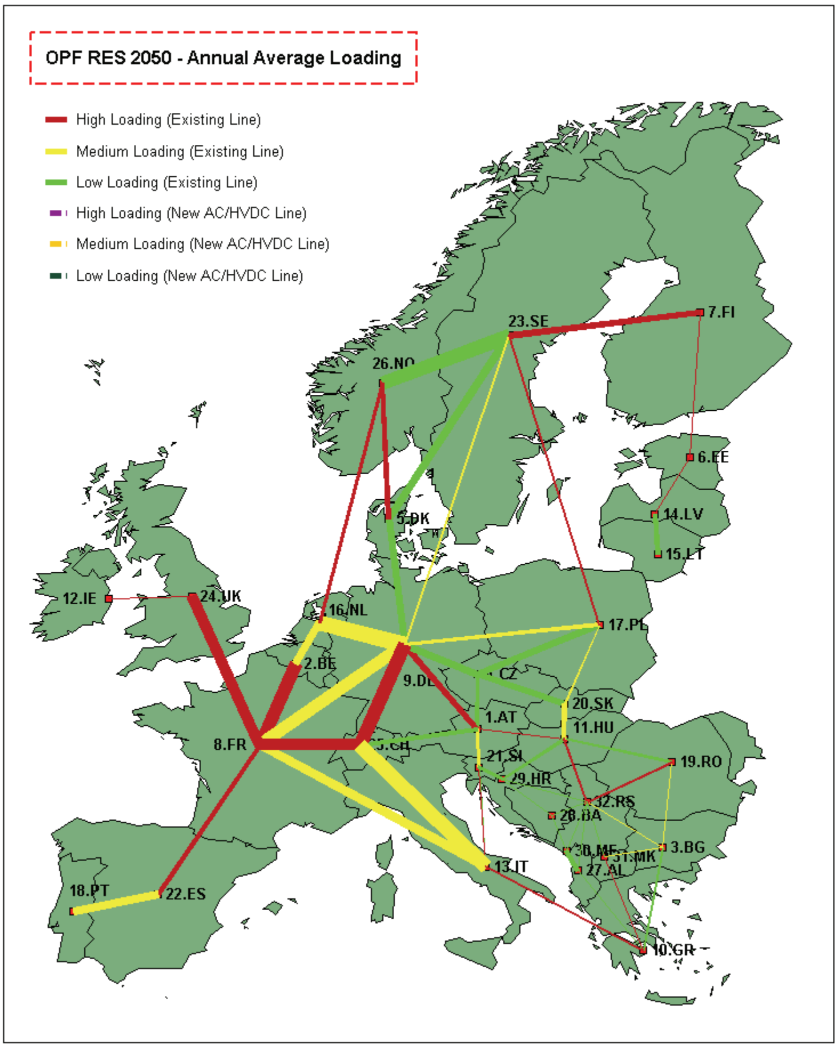

Figure 27: Annual Average Line Loading in 2050 (Base Case)

Figure 28 shows an investment scenario where 11 new 400 kV AC lines are built as indicated by the different colours. Furthermore, three HVDC lines are installed representing projects, which are already planned today (2012). In this case, generation costs decrease by 7% to 56.7 billion Euros per year.

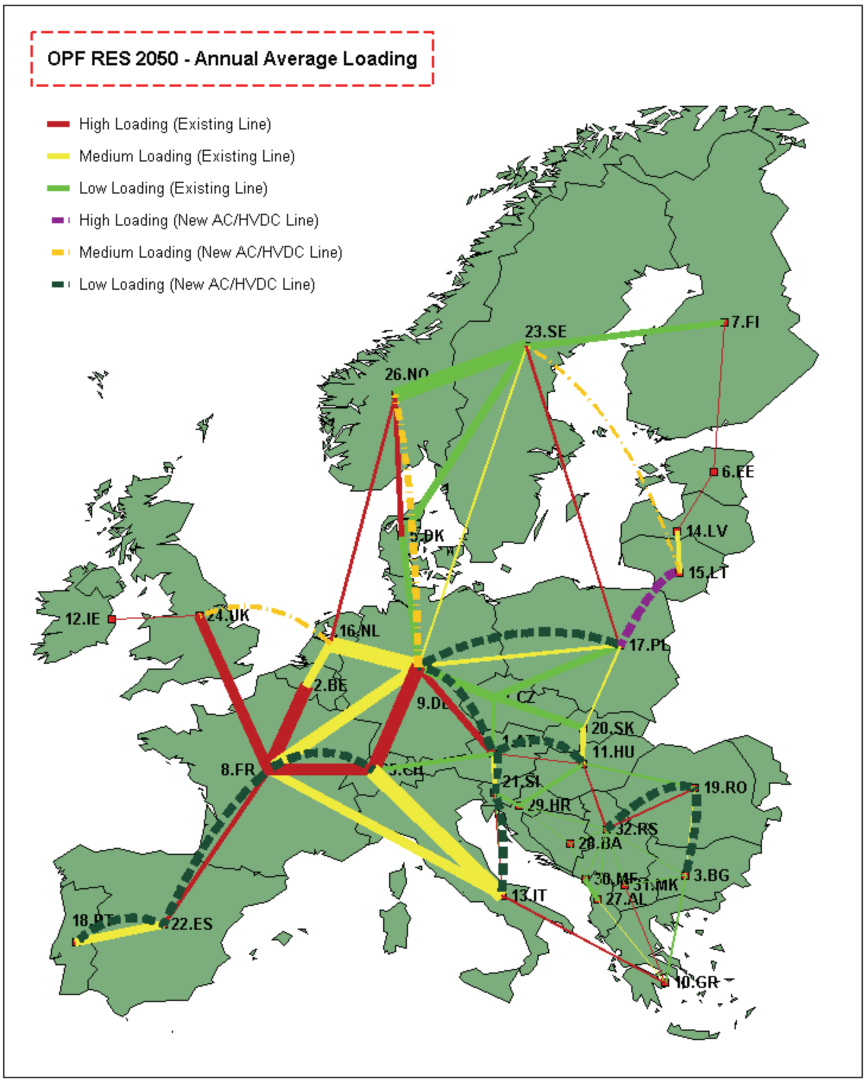

Figure 28: Annual Average Line Loading in 2050 (AC Expansion)

Eventually, Figure 29 shows the results for a last case, when the network is reinforced relying completely on HVDC technology. 14 new HVDC lines are built. This investment scheme leads to a decrease of generation costs by 11% to 54.3 billion Euros per year.

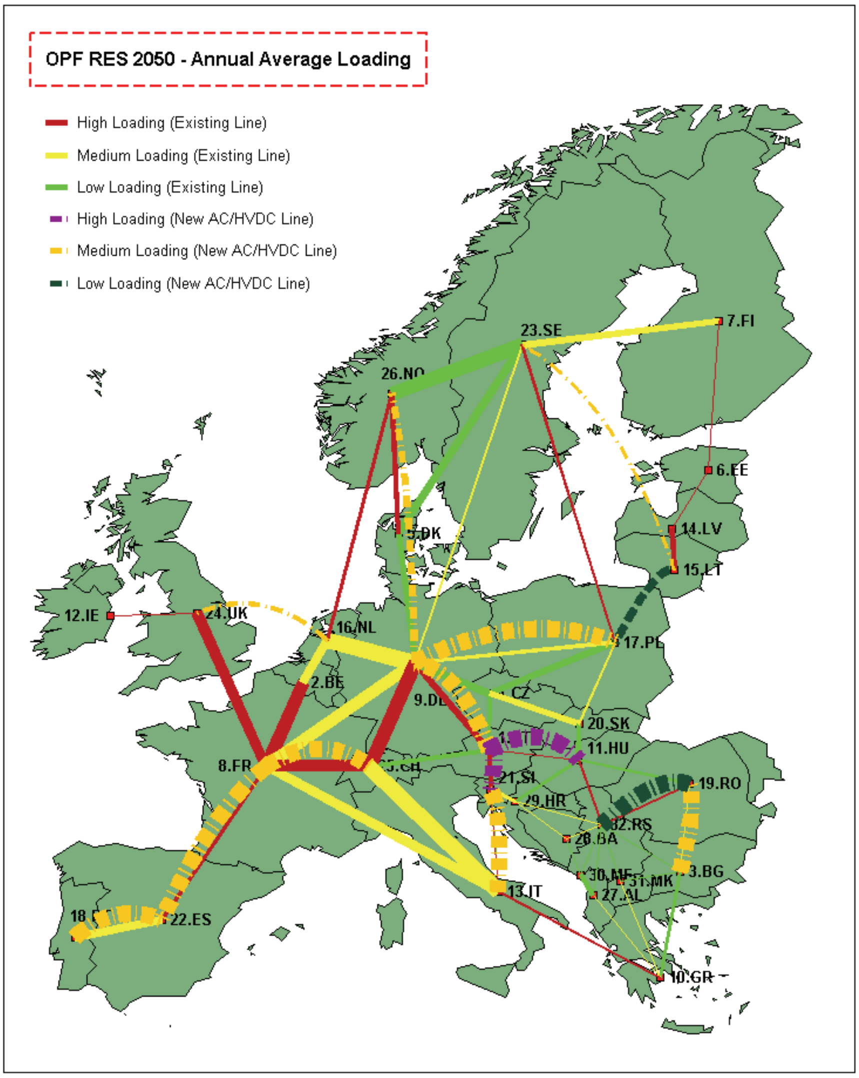

Figure 29: Annual Average Line Loading in 2050 (HVDC Expansion)

The results above are dependent on several parameters implicitly assumed for the development of generation and load as well as the spatial distribution of generation. However, it becomes obvious that the choice of technology and investment location will have an influence on generation costs and congestion. This mutual dependency indicates that different solutions are conceivable, i.e. prospective investment plans (preferred technologies and locations) might change with respect to the scenario assumptions.

The case studies have been evaluated within the FP7 project “Infrastructure Roadmap for Energy Networks in Europe (IRENE-40)” financed under grant agreement 218903. Results have been reproduced with kind permission. Details can be found under: www.irene-40.eu.

7. Options for future power production

7.1 Fossil with CCS including combined cycle plants

7.1.1 Introduction

Notwithstanding the desired long-term reductions of energy-related CO_2 emissions, it seems unlikely that fossil fuels will be entirely phased out by the mid-century, simply because of the substantial resources of coal and natural gas (both conventional and unconventional) worldwide. It is therefore important to look for ways to develop technologies that permit fossil-fueled plants to operate as (nearly) zero-emission power plants (ZEPPs). Apart from some specially designed (and somewhat more speculative) zero-emission cycles found in the scientific literature, there are typically three sorts of concepts that are applied to "capture" the CO_2 from fossil-fueled power plants:

- The first concept, usually referred to as *post-combustion*, does not intervene in the typical power-plant set up (both for coal-fired steam cycles and for gas-fired combined-cycle gas turbines —CCGTs), and aims at capturing CO_2 from the combustion exhaust gases.
- The second concept, mostly designated as *pre-combustion*, relies on the integrated gasification combined cycle (IGCC)[1] as basic starting point, but whereby the CO_2 is extracted from the synfuel (mainly CO + H_2) through a so-called shift reaction (i.e., by making the syngas react with steam) before the H_2 then is fed into a gas turbine.
- The third option, the so-called *oxyfuel* concept, is a set up in which combustion with pure oxygen organized, such that the exhaust gases only contain CO_2 and H_2O, leading to an easy separation of the CO_2.

After having captured the CO_2, it must be transported and then be disposed of, the latter usually called "storage" or "sequestration" (or less frequently, "disposal"). It is common to use the abbreviation CCS, although some people prefer to call it CCTS.

Figure 30 summarizes the concepts.

[1] An IGCC plant is roughly "similar" to a CCGT from a thermodynamic-cycle point of view, but it is a plant that produces its own "synthetic" gaseous fuel by gasifying coal or other solid fuels like biomass. The gaseous fuel is called syngas; it exists of a mixture of CO and H_2. (The gasification is done with a sub-stoichiometric amount of O_2, after having applied an air separation unit — ASU— to separate oxygen and nitrogen.) After thorough cleaning of this syngas gas, it is fed to a gas turbine, whose exhaust gases are then led through a recovery boiler that acts as heat source for a steam cycle, just like a CCGT. In summary, an IGCC is a CCGT with a substantial chemical installation to produce its own fuel. The exhaust gases of an ICGG contain CO_2, water vapor and N_2.

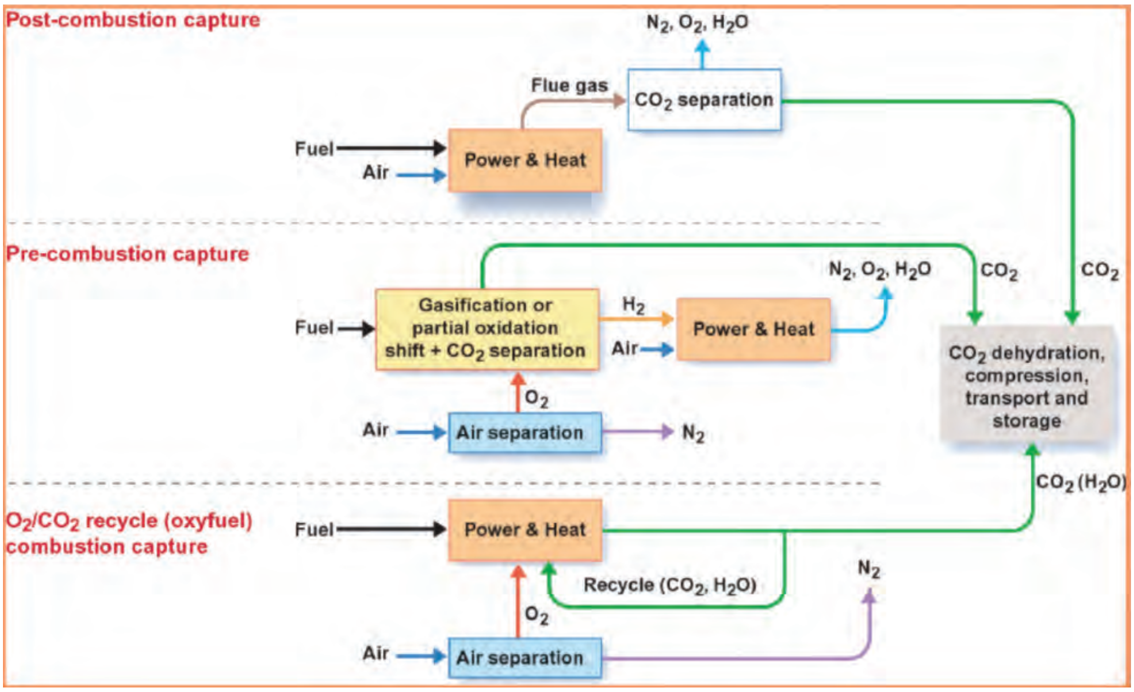

Figure 30: Overview of different CO2 capture methods in power plants. [VGB 2004, IEA, 2008 and IPCC 2005]

This Section only discusses the main principles. The reader is advised to consult the literature such as [IPCC, 2005], and the series of IEA publications, [IEA, 2004, 2008, 2009, 2011], for further details.

7.1.2 CO_2 capture

7.1.2.1 Post-Combustion

Post-Combustion is also often called an "end-of-pipe" technique or an intervention "downstream". The goal is to isolate the carbon dioxide from the exhaust gases, which typically contain 66.6 vol% N_2, about 16.7 vol% H_2O (vapor), about 5 vol% O_2 and about 11 vol% CO_2 for a typical pulverized coal super-critical 500 MW_e plant [MIT, 2007].[2] With this sort of composition, the low partial pressure of the CO_2 in the mixture (because of the large amount of N_2 still present) is an inconvenience. However, the separation process is well known in the chemical process industry; hence there are no difficulties in principle. The issue in CO_2 capture is the massive amount that must be handled. Indeed, a 500 MW_e coal-fired plant produces roughly 3 Mt CO_2 per year.

In summary, four separation processes seem to qualify as possible options:

- Separation through membranes;

[2] For CCGT power plants, the exhaust gases have a different composition, but the post-combustion principle is the same.

- Physical adsorption & absorption;
- Cryogenic distillation
- Chemical absorption in sorbents/solvents.

Of these possibilities, *chemical absorption in Mono-Ethanol-Amine (MEA)* seems to be the most convenient one at the time of writing. One part of the absorption method is the regeneration of the solvent, for which a considerable amount of heat is needed, basically provided by a bypass of the steam that is being withheld from the steam turbine. As an order of magnitude (and according to the overview in [IEA, 2011a]) for a variety of pulverized coal plants and fuels like bituminous coal and lignite, the output-power loss, or efficiency loss, amounts on average to about ¼ or 25%. The extra investment cost to add on a CO_2 capture facility is also considerable, and the relative increase in overnight cost per kW installed (also taking into account also the loss in net electrical power output) is, on average, of the order of about 75%. The relative increase in the levelized cost of electricity (LCOE, expressed per kWh_e) would amount to about 63%. For ultra-supercritical coal fired plants (USC) with bituminous coal, the numbers are somewhat more moderate: relative efficiency loss[3] of ~ 22%, increase of overnight cost of ~ 58% and relative increase in LCOE of ~ 46%.

7.1.2.2 Pre-Combustion

The pre-combustion scheme is related to the IGCC-type of plant. A solid fuel (coal, lignite, biomass and even waste) is gasified by partial oxidation, leading to a synthesis gas composed of mainly H_2 and CO. By means of a steam (or water vapor) shift reaction,

$$CO + H_2O\ (v) \leftrightarrow CO_2 + H_2,$$

the syngas is converted to CO_2 and H_2, from which CO_2 is relatively easily separated. The H_2 is the designated fuel for a hydrogen gas turbine, which exhaust gases are led through a heat recovery boiler, after which a typical Rankine cycle is put (as in common CCGTs). Now, but again according to [IEA, 2011a], the average relative efficiency loss is of the order of about 20%, while the increase in overnight cost (per kW installed) amounts to about 45% and the relative increase in LCOE (per kWh_e) would be roughly 40%.

7.1.2.3 Oxyfuel

In an oxyfuel plant, an Air Separation Unit (ASU) produces pure oxygen, which is then used to burn the coal. Because the temperature would be too high for

[3] The relative efficiency loss is expressed in % and not in %-pts here.

combustion with pure oxygen, a considerable fraction of the exhaust gases (consisting basically of CO_2 and H_2O vapor) are recycled towards the furnace/boiler (to serve as a temperature mitigating inert gas instead of the nitrogen normally present in air). As already said, the CO_2 is then easily separated. For an oxyfuel plant, we consider only an USC-type of plant (since routine commercial operation of the oxyfuel technology is perhaps still at least a decade away), for the "deterioration" of the performance. The relative efficiency loss would be about 23%, while the overnight cost would go up by about 62% and the LCOE by almost 50%. [IEA, 2011a]

7.1.2.4 Post-Combustion in CCGTs

Post-combustion with amines can also be applied to CCGTs, with no particular difficulty, although the partial pressure of CO_2 in the exhaust gases would be even smaller than in pulverized coal units (because of the larger air/fuel ratio in gas turbines). In this case, the characteristics are as follows [IEA, 2011a]: efficiency loss of about 15%, an increase in overnight construction cost by over 80%, and an increase in LCOE by 33%. Figure 31 presents a schematic summary of performance indicators according to [IEA, 2012]

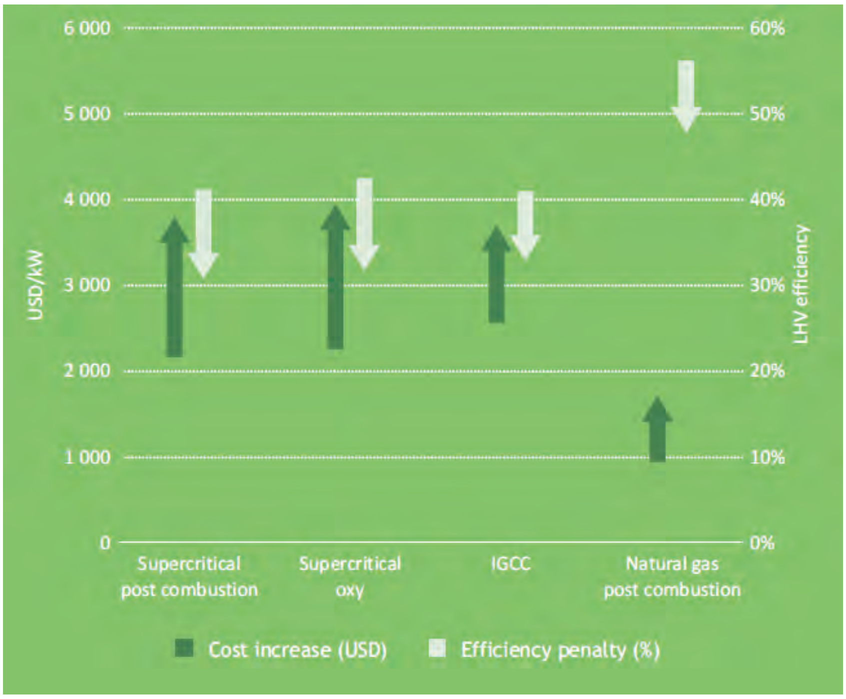

Figure 31: Cost increase and efficiency penalty; summary. Ref: [IEA, 2012]

7.1.2.5 Flexibility of plants with CO_2 capture

Application of carbon capture may hamper the flexibility and balancing characteristics of coal-fired plants and CCGTs. However, for the downstream technologies with post-combustion capture, it does not seem to be a major problem, and temporarily halting the CO_2 capture may even provide an interesting power boost, to be used as a “reserve” capacity. However, this sort of operation is dependent on the CO_2 prices in the Emission Trading Scheme (ETS), the fuel prices, the electricity prices and the performance of open gas turbines. [See e.g., Delarue, et al, 2012]

7.1.3 CO_2 transport

CO_2 can in principle be transported in refrigerated ships (somewhat similar to the LNG approach), which offers considerable flexibility. However, it is expected that most of the CO_2 will be transported by pipelines. This would occur in a supercritical state (with a density of a factor 10 higher than natural gas in pipe-line transport). CO_2 pipelines are similar to natural gas pipelines. Simulations show that in the long run (~ 2050) about 30,000 to 150,000 km pipelines may be needed in Europe, depending on the layout of the network. The cost of transport varies considerably depending on the distance, the amount and technical and financial parameters and would in the range of 1 – 6 USD/ton CO_2. [IEA, 2008]

The cost itself does not seem to be an overwhelming problem as such. One of the important issues to be addressed in the future, however, will be the actual investment in the infrastructure, including permitting and public acceptability. Faced with the “chicken and the egg” problem, this may be a serious obstacle. Also, what kind of CO_2-grid regulatory structure is one going to envisage? Will one accept private pipelines, or should the pipelines become part of a natural (i.e., regulated) monopoly, operated by a “CO_2-transmission-system operator”, with third-party access?

7.1.4 CO_2 storage & disposal

After capture, the CO_2 may be stored temporarily (or permanently) in the neighborhood of the plant where it was captured, although it is usually envisaged that the bulk amount will have to be transported and disposed of permanently in a more distant geological storage site.[4] For geological storage, several possibilities exist, such as depleted gas wells, CO_2 disposal combined with coal-bed-methane recovery from deep (difficult to exploit) coal seams, and in deep saline aquifers. Storage possibilities are scattered[5], but it seems that a huge potential storage capacity in Europe is available in the North Sea in saline aquifers (in Norwegian territorial waters). As there seems to be considerable public and political opposition against geological storage sites on land in several European countries, it does not seem unrealistic to consider long transport routes towards these North Sea sites, which are located far from human presence. This would mean, however, that the users of those disposal sites will have to pay the invoice to the owners and operators of those storage facilities.

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[4] We do not consider ocean storage. See the literature, e.g. [IPCC, 2005].

[5] The reader is referred to the bibliography for estimates of storage capacity.

A typical example is the case study performed by [Morbee, 2012], as shown in Figure 32.

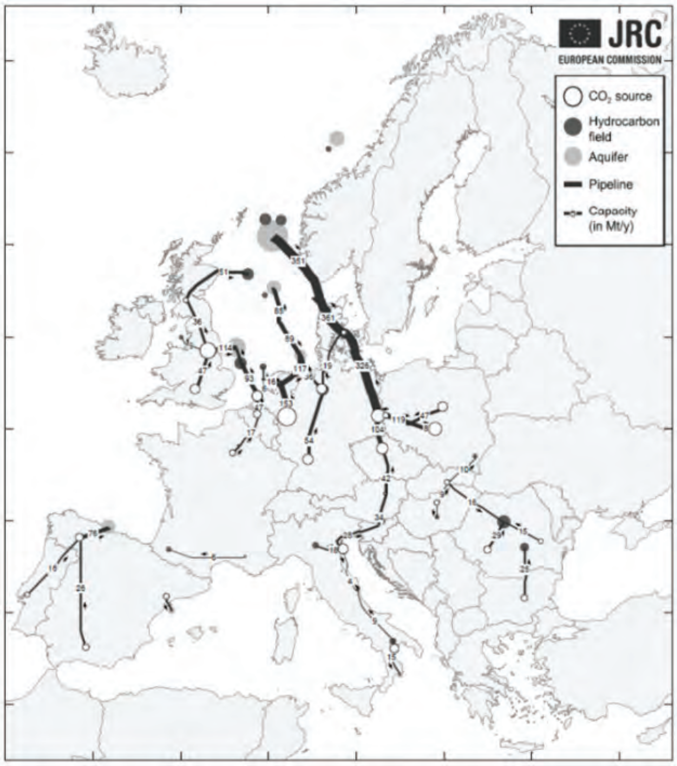


Figure 32: CO2 pipeline network in 2050, assuming joint international optimization. Total amount of CO2 captured and stored: 1145 Mt/y. (Ref: Fig 5.1 of [Morbee, 2012])

Costs for storage may vary according to different circumstances. For Europe, reasonable numbers seem to be in the range 10 – 20 USD/ton CO_2 [IEA, 2008].

7.1.5 Status and expectations of CCS

The latest long-term studies by the International Energy Agency consistently make the case that a massive reduction of energy-related CO_2 emissions, in order to reach the 450 ppm GHG in the atmosphere, requires the use of CCS. [IEA, 2010; IEA, 2011b]. Also, the cheapest scenario of the EU Energy Roadmap 2050 for drastic CO_2 reduction is the one where CCS is actively utilized. Likewise, in the Eurelectric scenarios “Power Choices”, CCS plays a prominent role. [Eurelectric, 2010]

Nevertheless, it must be observed that so far CCS has not been a success in Europe (and elsewhere). Although a considerable amount of EU money was allocated to CCS pilot projects after the outbreak of the economic crisis in mid-2008, it seems that the market and circumstantial signals are insufficiently convincing for investors. [von Hirschhausen, 2012] makes a harsh evaluation of CCS during the last decade. The analysis is sobering and many of the arguments merit most certainly reflection. However, their conclusion that there is basically no place for CCS is likely too negative, since it is simply extremely difficult to decarbonize our energy economy without CCS (and nuclear in some countries). The challenges would be far too daunting.

We believe that at least three problems can be mentioned (besides perhaps still some others), and should be resolved, for CCS to be a future success:

- Although clearly understandable because of the economic downturn, the carbon price in the EU ETS scheme is far too low for investors to make a business case. In addition, although the EU sets out a firm CO_2 reduction plan in its 2050 Climate Change Roadmap, the lack of credible international commitment after the UNFCCC COP meetings in Copenhagen, Cancun and Durban in 2009, 2010 and 2011, respectively, feeds the uncertainty for investors who have to make decisions for investment goods that are supposed to remain competitive for the next 40-60 years.
- The regulatory and market framework is insufficiently developed, certainly as far as CO_2 transport and storage is concerned. Furthermore, public opposition against CO_2 storage seems to pick up, being supported by the (local) decision makers. A clear framework and information campaign seem to be conditions sine qua non for at least the beginning of success for CCS.
- Technically, one has tried to do too many things simultaneously, by supporting three developments in parallel, of which some are premature. As a consequence, the support money has been spread too thinly. On should certainly have supported pre-combustion and oxyfuel by moderate R&D funds, but the big money should have been reserved for demonstration projects based on post-combustion, the technology that is easiest technologically and closest to the market. After the (almost guaranteed) success with capture, CO_2 transport and storage could have been developed in parallel. And after having all infrastructures in place, the more advanced capture technologies should then receive the bulk of the development and demonstration attention.

It is not too late yet for CCS to be part of the future technology base of carbon free energy-conversion equipment, but resolve and a clear framework are urgently required.

7.2 Nuclear

7.2.1 Generations of Nuclear Power Plants

Nowadays, the term nuclear power refers to energy generation by fission. An industrial application of nuclear fusion is not yet in view. Light Water Reactors dominate the world-wide fleet of nuclear power plants. Some older gas cooled reactors are being phased out. In some countries, heavy water moderated and cooled reactors are successfully operated. Apart from this, there are some high-temperature pilot plants and breeder reactors that can be regarded as generation IV systems.

There is a common categorization of nuclear reactor types, referring to them as belonging to a certain generation. Current nuclear power plants are considered to belong to the so-called reactor generation II, which distinguishes them from early prototype plants (generation I). This category comprises serial units commercialized by industrial vendors since the sixties and seventies. All power reactors currently operated in Switzerland belong to this generation. Generation III refers to new, significantly safer reactor types. Their main characteristics are a substantial enhancement of the safety systems employed to avoid a core damage and the installation of design features that are capable of confining the radioactive inventory inside the plant even in case of a core damage. In Switzerland, the safety standard of current generation II plants has been increased step-by-step to the one of generation III by comprehensive safety upgrades that are possible with current technology.

The development of generation IV reactors is mainly driven by the motivation to enhance sustainability. The particular goals are: (1) reduction of the specific fuel consumption by consequent use of non-fissile uranium (U-238) and thorium (Th-232) which are by two orders of magnitude (a factor of 100) more abundant than fissile uranium (U-235), making up only 0.7 % of the natural uranium, (2) transmutation, i.e. reduction of very long-life components in the nuclear waste by fission with fast neutrons, (3) enhancement of proliferation resistance and (4) generation of process heat on a high temperature level, for example to produce hydrogen or other synthetic fuels. For physical reasons, the best way to achieve these goals consists in a departure from the use of water (or heavy water) as a reactor coolant. Consequently, the design and physics of generation IV reactors differ considerably from common light water reactors. Metallic melts of sodium, lead, lead-bismuth eutectic or helium gas are applied. An interesting alternative concept is the molten salt reactor where the fuel itself is liquid.

The new reactor concepts and coolants offer a number of inherent advantages in terms of safety. It is expected that these features can be exploited to further improve plant safety. Nevertheless, one has to be careful, since inherent safety features always address only certain selected aspects and the radioactive inventories are high, independent of reactor type. Of course, there are certain differences. Furthermore, the level of safety achieved by generation III, expressed in low core damage frequencies and mature concepts for the retention of radioactive substances even in case of core damage, makes it very challenging for generation IV to compete and to reach a similar or, as it was set as a goal at the begin of the generation IV development, an even better degree of safety. This is one of several reasons why it will still take a considerable time before generation IV plants are commercially available.

7.2.2 Safety

7.2.2.1 Radioactive inventory

Before discussing reactor safety, the nature of the radioactive inventory of a reactor core has to be understood. By far the highest quantities of radioactive material are created as a product of the fission reaction which is the source of the generated energy. Fission products are extremely radioactive and also responsible for the decay heat production. With a half-life period of 30 years, caesium-137 is one of the most prominent fission products. All others decay considerably faster and pose therefore a smaller risk. Others, on the other side, have such a long half-life period that their radioactivity is comparatively low. Fission products pose extreme requirements on the retention abilities of the barriers in deep geological depositories for periods in the order of one thousand years, which is fortunately much less than the durability of casks currently proposed for the enclosure of the highly active waste.

A second group of substances is generated by the absorption of neutrons in non-fissile components of the nuclear fuel. These are isotopes of elements beyond the end of the original periodic system of elements (Plutonium, Americium, Curium, and Californium). There are no means to completely exclude their formation by the mentioned side reactions. Still, it has to be noted that the quantity of minor actinides is lower by about three orders of magnitude if Thorium is used instead of Uranium fuel, which makes the Th-232 / U-233 cycle somewhat attractive from the point of view of waste reduction. Many actinides are strongly radiotoxic alpha emitters, posing high health risks when incorporated, and have long half-life periods in the range of thousands of years. Most prominent in this respect is Plutonium-239 with 23’500 years. Due to their slow decay, they do not significantly contribute to the decay heat production, but their presence challenges the waste disposal concepts, because the necessary enclosure time exceeds the durability of disposal casks. Fortunately, host rocks available for deep geological depositories, such as opalinus clay, show a strong retention capability by adsorbing and absorbing the actinides in their crystal structures. This is an important element of the proposed concepts for deep geological waste disposal, e.g. in Switzerland.

The third group of radioactive isotopes consists of construction materials that become radioactive when irradiated by neutrons. The inventories are very small compared to the spent fuel and the fuel in the reactor during operation. They are found in the low and medium active waste and are subject to protective measures during decommissioning, but do not play a significant role during accidents.

7.2.2.2 Safety barriers

The retention of the radioactive inventory is the main safety concern in nuclear power generation. Therefore, irrespective of reactor type, a nested system of safety barriers has to prevent the release into the environment. “Nested” means in this context that the failure of barriers does not lead to a substantial release of radioactive material as long as at least one barrier stays intact. In light water reactors, the barriers are (1) the fuel rod shell, called cladding and, to a certain extent, the retention inside the solid ceramic fuel pellets, (2) the walls of the reactor vessel and of the primary cooling circuit and (3) the hermetic reactor building called containment.

The requirements concerning the retaining function of the barriers are high, because some of the fission products are volatile. These are radioisotopes of the noble gases Xenon and Krypton, as well as the extremely dangerous radioactive Iodine 131 and Caesium 137, which evaporate if the fuel is not cooled appropriately and form aerosol particles that can be transported over large distances. Additionally, barriers are endangered by the decay heat production of the fission products themselves. Safety systems are therefore needed to protect the barriers from internal threats. In the last decades, it has become increasingly clear that external events can also pose a risk to the barrier system, and, as it was illustrated by the Fukushima accident, also to safety systems installed to protect them. Barriers, as well as safety systems and measures to protect them, constitute the concept of “defence in depth”.

“Defence in depth” is the necessary basis for the safety of any reactor type. The technical solutions for its implementation vary for different concepts. Some coolants, like water or helium, require a high reactor pressure and the protection against breaks of the coolant circuit requires much more effort than liquid metals which have a high boiling point and whose reactor vessel can stay close to ambient pressure. On the other hand, molten sodium is chemically very reactive and requires special solutions to avoid damages to the reactor as a consequence of contact with air or water. Some high-temperature reactors can remove decay heat reliably by thermal radiation, which is regarded as an inherent safety feature, etc. The details will be discussed in the section with the individual descriptions of the various concepts.

There is no technical solution in sight to speed-up the decay or to reduce the lifetime by conversion into nuclides that decay faster, unlike in case of the transmutation of minor actinides.

7.2.3 Safety of currently operated plants

7.2.3.1 Generation II as initially designed

All nuclear power plants in commercial operation belong to generation II (there is a discussion concerning the Japanese ABWRs whether they already belong to generation III, which would be the only exception). From the very beginning, these plants were equipped with a reliable reactor protection system as well as redundant emergency core cooling systems to adequately address the most important classes of accidents caused by internal accident initiating events leading to (1) uncontrolled chain reactions (RIAs = Reactivity Induced Accidents) and (2) loss-of-coolant accidents (LOCAs). External initiating events have also been addressed, but earthquakes, airplanes and flooding resistance have not been taken into account sufficiently. Furthermore, there were few redundancies; many stations had just two strands of redundant emergency systems, as was also the case in Fukushima due to the lack of continuous upgrading. The biggest difference from today’s philosophy was the view on core damage and consequent melt-down. For these accidents – either caused by the failure of all redundancies of the emergency systems or by external impacts unrelated to the design – no measures for an internal emergency response were implemented, neither in terms of guidelines and training for operators nor in terms of hardware. It turned out that Fukushima also had grave deficiencies in this area.

7.2.3.2 Generation II today

Currently operated generation II plants have been upgraded to a varying extent. An internationally recognized leader and trendsetter in reactor safety is Germany. Switzerland followed all modern developments in this sector and also contributed with its own research to nuclear safety which is mainly carried out at the PSI.

The upgrades – aiming at an enhancement of design basis safety to meet the requirements – start with retro-fitting measures according to the so-called single failure criterion and lead to additions of redundant strands in the emergency core cooling system as well as in the emergency power supply. The main upgrades which address core damage accidents start with hydrogen recombiners located in the containment to eliminate the risk of Fukushima-like explosions. They continue with installations to re-flood the reactor or the reactor cavern to stop the progression of a core melt. The final measure consists of prepared nozzles for an injection from mobile pumps and fire-fighter equipment and filtered venting devices which allow the reduction of containment pressure in time with a minimum radiological impact on the exterior of the plant. It is very likely that the presence of such systems would have prevented the core damage in Fukushima.

To summarize, whenever generation II plants have been upgraded with respect to the state-of-the-art, they possess a high degree of protection against core damage in case of accidents caused by internal and external initiating events. This leads to low theoretical frequencies (probabilities) of a core damage in the range of around once in 100’000 years for the old Swiss plants. Furthermore, systems and guidelines are implemented to confine the radioactive inventory also in case of core damage inside the plant and to avoid or at least mitigate the consequences to the environment and population. The frequency of a large release of radioactive material is therefore even lower by about one order of magnitude.

These results cannot be applied in general to all nuclear power plants in the world, since the status of upgrades varies considerably. The European Stress Test is the first international activity aiming at a definition of binding requirements for upgrades. Earlier on, international organizations such as IAEA and WANO were only issuing recommendations – the legally binding requirements were defined on a national level.

7.2.3.3 Generation III

The development of generation III started with the main target to enhance the safety of light water reactors in such a way that it is possible to confine the radioactive inventory in the containment under all imaginable accident conditions to a degree that external emergency measures, such as evacuation of the inhabitants or the distribution of iodine pills, would never be necessary. There were two main lines of innovation, so-called evolutionary and revolutionary concepts.

Evolutionary means that the core damage frequency was to be decreased significantly by strengthening the conventional barriers and safety systems. For the then very unlikely case of a core meltdown, an installation was developed that is able to receive the molten material after core damage in a way that the containment stays intact and large releases of radioactive material are prevented. The EPR under construction in Finland belongs to this group.

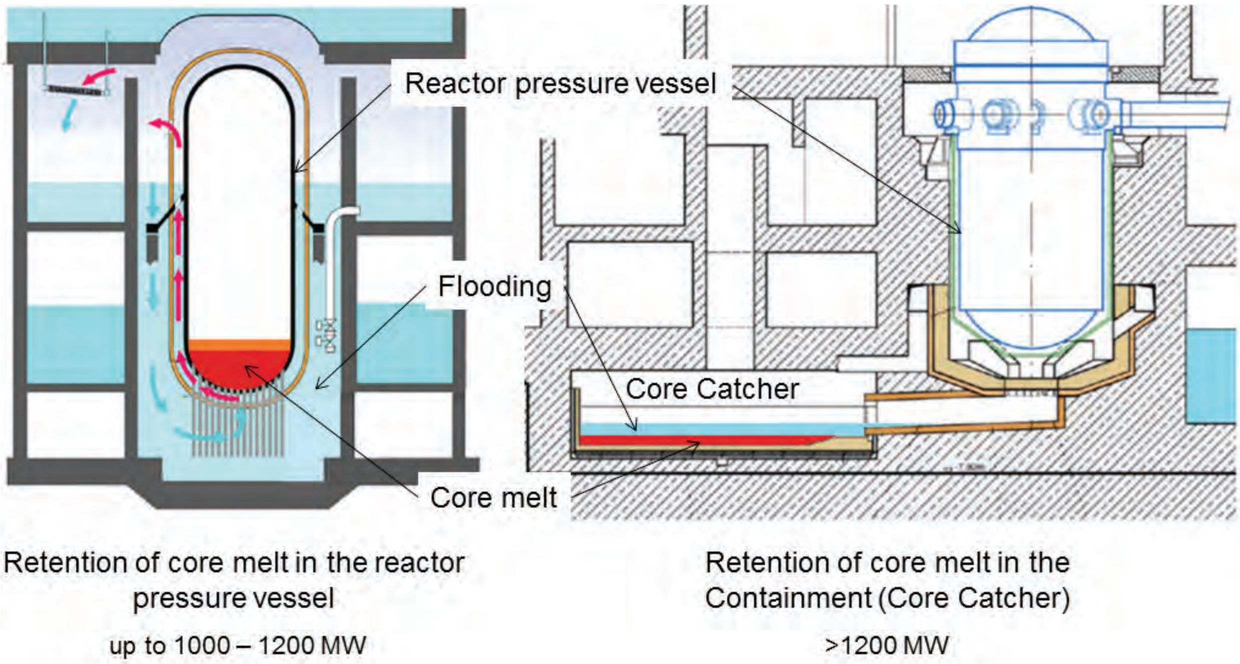


Figure 33: In-vessel molten core retention and ex-vessel core catcher in Gen III systems. Sources: Left (simplified): Zoran V. Stosic, Werner Brettschuh, Uwe Stoll: Boiling water reactor with innovative safety concept: The Generation III+ SWR-1000, Nuclear Engineering and Design 238 (2008) 1863-1901. Right (simplified): Manfred Fischer: The severe accident mitigation concept and the design measures for core melt retention of the European Pressurized Reactor (ERP), Nuclear Engineering and Design 230 (2004) 169-180.

The developers of the so-called revolutionary concepts aimed at deterministically excluding core damage by extremely reliable passive safety systems. Power plants following this development strategy are often referred to as generation III+. The biggest bottleneck of classical safety systems, e.g. the emergency core cooling, is the reliability of the external power supply. This problem was solved by introducing systems that perform the required safety functions without external power. Examples are gravity driven reactor flooding, depressurization of the reactor to enable passive flooding and heat removal from the containment by gravity-driven natural circulation. It is important that there are strict requirements concerning passivity: Systems that need operator actions for their control are not regarded as passive safety systems.

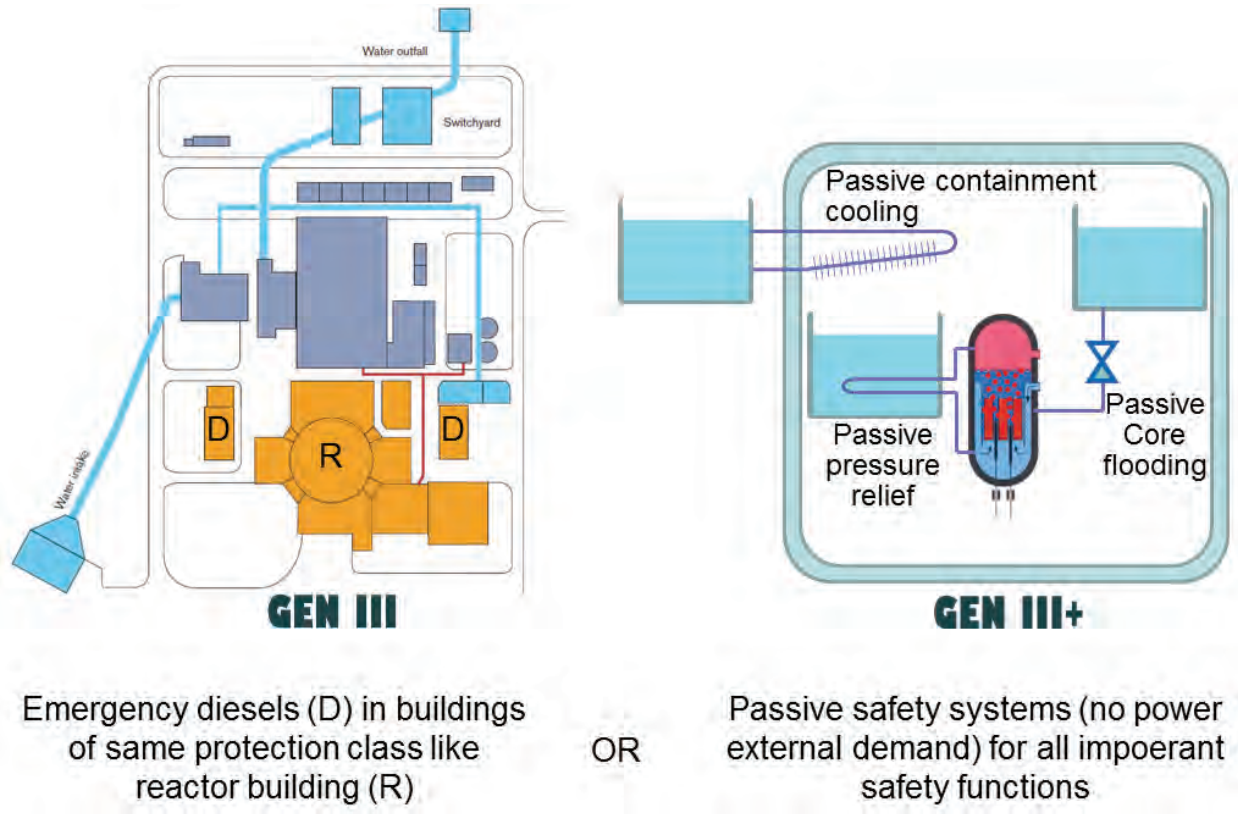


Figure 34: Passive systems applied in Gen III for the most important safety functions.

For fundamental reasons, it was not possible to demonstrate that the probability of a core damage turns to zero by the use of passive systems, even though very low core damage frequencies are achieved, which are around once in 10 million years. For this reason, plant developers favouring passive safety also decided to implement a core retention concept. Finally, all generation III plants offered by the main vendors worldwide include systems for a safe enclosure of a core melt. This may be done by an external reactor pressure vessel cooling, if the thermal power of the reactor allows removing the decay heat through the reactor wall. It requires a flooding of the reactor cavern, which is ensured by valves that open automatically when the temperature in the reactor cavern starts to increase, and a gravity driven inflow from a neighbouring storage pool. For reactors with a thermal power exceeding 1’000 – 1’200 MW, the reactor pressure vessel represents a too high thermal resistance and inevitably fails when molten core material starts to accumulate in the lower plenum of the reactor. For this case, external core catchers were developed. In the latter case, the core material is also cooled by a passive flooding from a neighbouring pool.

Secondary goals were concerned with enhancements of efficiency, reliability, the reduction or at least limitation of investment costs, standardization by the creation of product lines. Tremendous efforts made in the area of safety led to an increase rather than a decrease of capital costs. Efficiency gains are naturally limited to those gradual improvements achieved by a consequent use of available modern techniques concerning the optimisation of Light Water Reactors. There is no qualitative leap comparable to the one that is anticipated in connection with the development of generation IV and a closed fuel cycle.

Some research programmes aim at a further perfection of generation III. There are concepts of so-called high-conversion Light Water Reactors that gradually enhance conversion of fertile to fissile material by applying the concept of dense lattice fuel elements, leading to a faster neutron spectrum. There are promising results that show the general feasibility of reactors capable of iso-breeding, which would create a certain competition with generation IV. These approaches are combined with a review of the potential of a use of the thorium cycle.

Furthermore, a continuation of a further improvement of the safety parameters of generation III is also on the agenda, especially concerning the perfection of passive safety systems and a consequent use of passive safety for achieving economic advantages. One particular goal is a fully passive long-term ultimate heat sink for the case of a damaged core confined in the containment, as a target of high attractiveness after Fukushima.

7.2.3.4 Generation IV

Generation IV is a collective term for reactor types under development which should achieve a quality leap concerning the sustainability of the fuel cycle. Furthermore, goals were set in regard to an improvement of economy, safety and proliferation resistance. Some reactor types follow the goal to go beyond electricity generation by producing process heat on a high temperature level. The R&D work is coordinated by the Generation Four International Forum (GIF), with Switzerland as a member. Six different reactor types were selected as main lines of the development. Different development teams favour solutions that may substantially vary in some design details. All generation IV concepts have in common that none of them is yet mature for a commercial use. Some of the concepts were tested in the past and feasibility was demonstrated in principle. These projects left open a number of questions and problems concerning reliability, safety and economy, which are now addressed by the R&D on generation IV. It is expected that the huge experience accumulated in the past, combined with newest results of research in reactor physics, thermal hydraulics and nuclear materials, together with today’s capabilities in computer simulation allow to resolve these remaining issues. Some singular projects on prototype facilities are on the way.

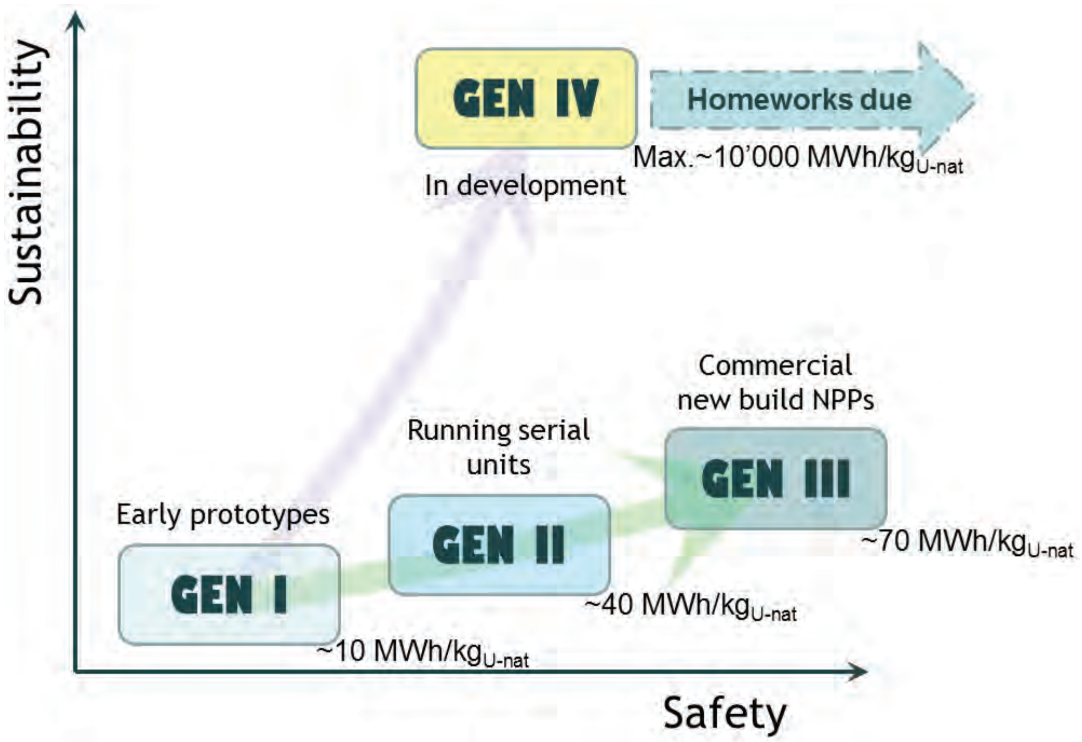


Figure 35: Reactor generations in the coordinate system "sustainability" and "safety"

7.2.4 Fuel sustainability

7.2.4.1 Generation of new fissile material

Some of the reactor types – Sodium cooled Fast Reactors (SFR), Lead or Lead-Bismuth cooled Fast Reactors (LFR), Gas cooled Fast Reactors (GFR) and the fast version of the Molten Salt Reactor (MSR) (summarized under generation IV) – represent so-called “fast reactors”, which means that the neutron moderation, i.e. the slow-down, is suppressed as much as possible by a selection of an appropriate coolant. Consequently, neutrons generated in an act of fission are inducing the next fission reaction almost with the energy at which they were born, i.e. as fast neutrons. This, in turn, makes it possible to generate significantly more new fission neutrons than in case of slow neutrons. After subtracting losses and the one neutron that is needed for the next act of fission, more than one neutron remains for the conversion of either U-238 into Pu-239 or Th-232 into U-233. In the end, more new fissile material is produced than consumed. This process is called breeding. The sustainability is significantly improved by the fact that non-fissile nuclides of uranium and thorium, which are by more than a factor of 100 more abundant on earth than fissile uranium 235, can be used. This alone extends the reach of the resources of fissile material by about the same factor. In reality, the available resources multiply by many more orders of magnitude, because ores with extremely poor uranium content and vast thorium reserves become utilizable, this would make almost inexhaustible fuel resources accessible.

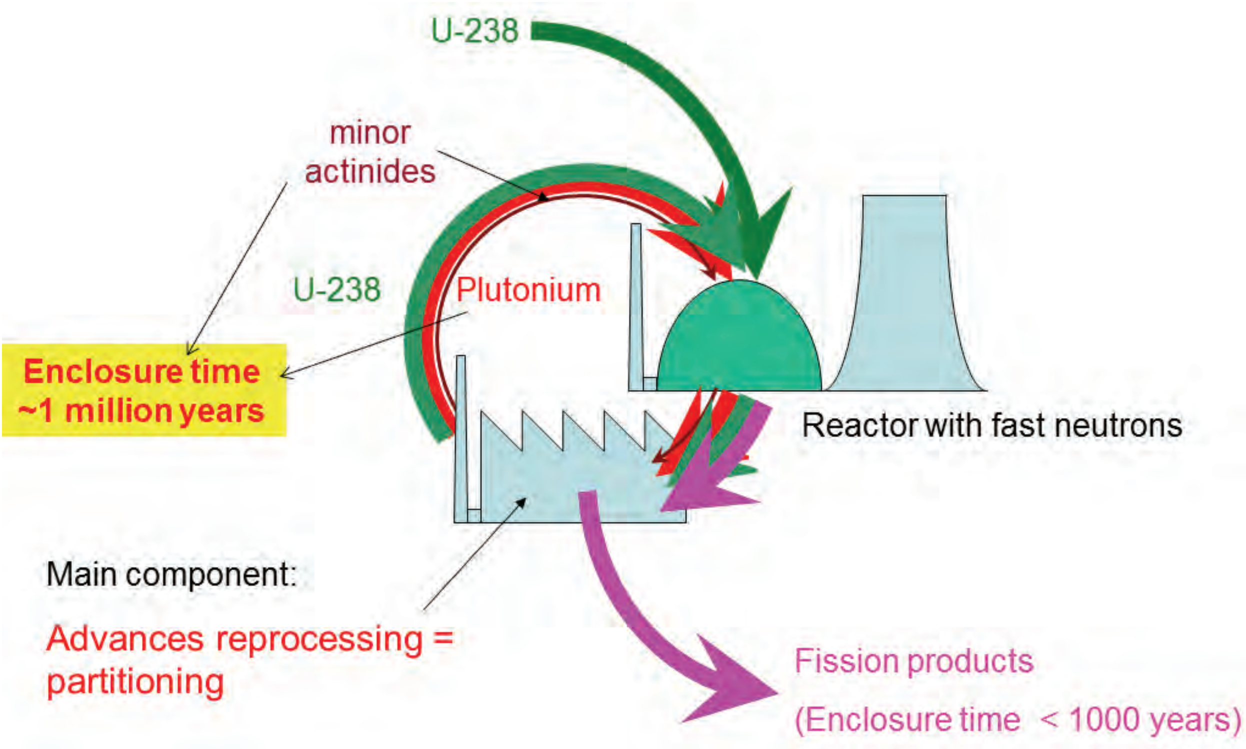


Figure 36: Scheme of a closed nuclear fuel cycle

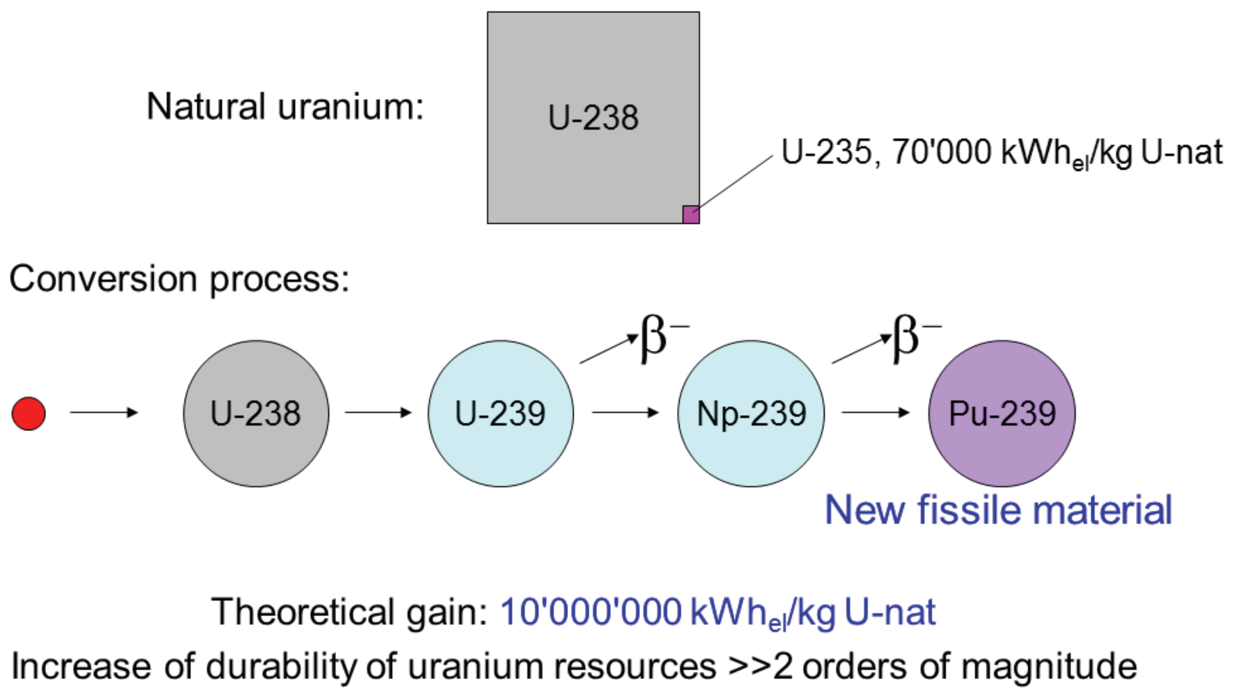


Figure 37: Conversion process in fast reactors as source of long lasting fuel resources.

Reactor types of generation IV that employ slowed down neutrons, namely the Very High Temperature (gas cooled) Reactor (VHTH), the Supercritical Light Water Reactor (SCLWR) and those versions of the Molten Salt Reactor (MSR) that use a neutron moderator, provide enhanced fuel efficiency, too. Nevertheless, the efficiency gain is significantly lower than in the case of fast reactors. The main effect is the higher thermal efficiency achieved by the higher temperatures of the reactor coolant. In this regard, the Molten Salt Reactor (MSR) with thorium-uranium 233 fuel is an exception because of the excellent properties of uranium 233 in terms of the neutron reproduction rate, which also allows breeding with slow or medium fast neutrons (so-called “iso-thermal neutrons”).

7.2.4.2 Transmutation

The transmutation of actinides is a way to reduce their lifetime by converting them into fission products. The fact that only about half of all actinide isotopes are fissile with thermal neutrons makes it necessary to resort to reactors with fast neutrons for this purpose. Therefore, fast reactors can combine breeding with transmutation. In thermal reactors, e.g. the current light water reactors, the non-fissile actinides would further accumulate instead of being eliminated.

7.2.4.3 Reprocessing as a complement to generation IV

7.2.4.3.1 Hydro-metallurgical processes

It has to be noted that fuel sustainability, as well as issues of proliferation safety, are closely connected to the concept of a closed fuel cycle based on advanced reprocessing. Without reprocessing, conversion and transmutation hardly makes sense. Today, reprocessing is a procedure that separates the unused uranium and the generated plutonium from the spent fuel (the so-called PUREX process), leaving behind highly active nuclear waste consisting mainly of fission products and higher conversion products from non-fissile uranium 238, the minor actinides, as outlined in the section “radioactive inventory”. This waste is vitrified, i.e. it is mixed with molten glass and cast into stainless steel flasks, which finally have to be disposed of underground. The separated uranium and plutonium can be reused as a new fissile and fertile material. This is partially done by the use of mixed oxide (MOX) fuel in countries that have not abandoned reprocessing. In Switzerland, a 10 years moratorium on reprocessing is effective since 2006, whereas in Germany it is forbidden since 2005.

The reprocessing also needed to close the fuel cycle for the minor actinides is called partitioning. In this case, the waste stream from normal reprocessing is treated again in a different chemical process that separates the minor actinides from the fission products. Only the latter have to be vitrified. The resulting high-level waste requires enclosure times of less than 1000 years to decay to levels of radio toxicity characteristic of the uranium ore taken out to produce the initial amount of fuel the waste stems from. This is much shorter than the time required for the actinide containing waste from today’s reprocessing.

A high proliferation resistance can be achieved by a process that removes plutonium and minor actinides in one step, because the higher activity of the minor actinides makes it very difficult to extract plutonium from the product stream in an unauthorized way for nuclear weapons. This kind of advanced partitioning process is under development (Group Actinides Extraction, GANEX), being developed by the French-Japanese-US Global Actinide Cycle International Demonstration (GACID) consortium. This contaminated plutonium can be used in new fuel elements. When placed in a reactor capable of transmutation, the supply with fissile material and the loading of the minor actinides is performed in one step. The fuel, regardless of its chemical or mechanical form, remains radioactive enough to guarantee a high protection against theft all along the entire fuel chain.

7.2.4.3.2 Pyro-metallurgical processes

A second technology line for reprocessing is based on dissolving the spent fuel in a molten salt and treating it with electrochemical methods. As, for example, in the copper industry, electrolytic dissolution and deposition can be used to separate elements by their electrochemical potential. Nobler elements are collected at the cathode of a molten salt electrolysis cell first, less noble elements only later at higher voltages. This process can be used to extract uranium, plutonium and other actinides as well as any other interesting material from the melt, which will finally contain only useless fission products.

It is a very compact process with a number of advantages: (1) The molten salt is less perceptible to radiation damage compared to the organic extracting agents used in hydro-chemical separation processes, (2) some fuels that are difficult or impossible to access by chemical digestion with nitric acid, like coated particles of High-Temperature Gas-cooled Reactors, can be treated, and above all, (3) the product streams containing fissile material carry a considerable radioactive contamination by minor actinides, which is seen as an obstacle for an unauthorized use of fissile material.

Pyro-metallurgical reprocessing was tested as integrated systems at the site of some prototype breeder reactors such as the BN600 in Russia. There is therefore some industrial experience, although the methods are less developed than the hydro-metallurgical ones. In combination with Molten Salt Reactors, this technology can become the silver bullet towards a closed fuel cycle with high proliferation resistance.

7.2.4.4 Safety

Generation IV reactors still have to be developed that achieve the safety level of generation III types currently available for newly built nuclear power plants. In case of Sodium cooled Fast Reactors (SFR), the chemical reactivity of molten sodium with air and water, as well as issues concerning the stability of the chain reactions are to be resolved. Lead and Lead-Bismuth cooled Fast Reactors (LFR) require the solution of corrosion problems of the construction materials, Gas-cooled Fast Reactors (GFR) pose challenges to the emergency core cooling concepts, and Molten Salt Reactors have to prove the efficiency of their barrier concept, just to mention a number of most relevant challenges. On the other hand, there are numerous advantages such as the absence of a high reactor pressure and therefore the possibility to deterministically exclude loss-of-coolant accidents in pool-type reactors cooled by a molten metal, excellent heat removal properties of the new coolants, high thermal inertia of the large coolant pools, etc., which are exploited as inherent safety features.

7.2.5 Other concepts outside generation IV

7.2.5.1 Travelling wave reactor (TWR)

The most prominent example of a reactor concept that allows breeding and, to a certain extent, a gradual transmutation of the waste without reprocessing is the travelling wave reactor (TWR), whose development is supported by Bill Gates. It was proposed by Feinberg already in 1958 and the R&D is carried out by TerraPower with funding from Bill Gates. From the point of view of fuel technology, reactor physics and cooling, as well as in terms of its contribution to sustainability and proliferation resistance, it strongly resembles sodium cooled fast reactors (SFR) of generation IV.

The core of the TWR has a large extension in one direction (e.g. vertical). It is mainly charged by fertile material, i.e. uranium 238. There is enough fissile material to start a chain reaction only in a small lower part. The neutrons escaping from this region towards the neighbouring zone with fertile material cause the conversion of a part of it into fissile plutonium. In this breading zone, the chain reaction starts up when enough plutonium has been accumulated, while it dies out in the zone below, because there the fuel expires. The fission zone, where a chain reaction is possible, moves through the entire core in this way, producing energy potentially for 2—3 decades, leaving behind the spent fuel elements. Potentially, such reactors might be also designed for a Th-232 / U-233 cycle. This concept has to rely on fast neutrons and consequently the coolant must be a bad moderator. Liquid sodium is the most prospective candidate.

In view of the use of sodium, the advantages and disadvantages of the TWR are similar to those of the sodium cooled fast reactor (SFR). Many advantages arise from the fact that the reactor has to be charged with fuel only once before commissioning. Refuelling and the associated outages are not needed, which simplifies the technology. Still, outages for inspections and periodic safety assessments will not be avoidable. The operating cycle leaves behind a full core load of high level radioactive waste.

Small Modular Reactors

There is a large number of developers that advertise so-called Small Modular Reactors. The working principle and therefore also safety and sustainability characteristics vary widely. Among the concepts, there are Light Water Reactors as well as various combinations of innovative fuel concepts with a range of coolants and sometimes moderators. Often, SMR belong to this class. It goes far beyond the scope of this text to present all existing reactor types in detail. Modular in this context means that a large power plant output is achieved by uniting a number of small reactors, which provides to possibility of a stepwise extension towards a high installed power by successively adding reactor units. It is stated that this will reduce the initial investment, which is sometimes regarded as a considerable economic obstacle for new nuclear installations. As soon as the power plant starts operating after the commissioning of the first modular units, the profit from the early turnover can be allocated to extend the installed power.

From the safety point of view, the low unit size makes it easier to design passive or inherently safe features for the reliable removal of the decay heat, because it is proportional to the thermal power of the core.

It is a clear disadvantage that for many proposed solutions there is no or hardly any operational experience available. There are many “paper reactors” among the concepts discussed. For this reason, the cost claims of potential vendors and the efficiency of the power conversion remain unproven for many of the concepts. Note that “economy of scale” as a quite broadly recognized approach to ensure a profitable operation of power plants would be abandoned with the move towards Small Modular Reactors. Open questions are therefore connected with the acceptance of a higher number of reactors for the same power output, the likely higher impact of licensing costs and operation costs in general. Furthermore, the theoretical frequency of severe accidents has to be multiplied by the number of reactors (e.g. like the Core Damage Frequency), which poses very high requirements on the safety of each single reactor.

7.2.5.2 Accelerator Driven Systems (ADS)

An assembly of fuel elements containing material for transmutation (plutonium, minor actinides), which is not able to produce a self-sustaining chain reaction, is supplied with neutrons from a spallation source driven by a large proton accelerator. The core of the reactor amplifies the neutron flux from the spallation source because it still has some neutron-multiplying properties. It works with fast neutrons needed for an efficient transmutation of the long-lived waste. The process is exothermal, the reactor produces more energy than the accelerator consumes. The excess can be fed into the net.

The fact that the core cannot sustain a chain reaction on its own makes reactivity-induced accidents impossible. This eliminates the need for negative feedback coefficients from the beginning, which are difficult to achieve in reactors with fast neutrons (see section 5.1.2). This was the main motivation of Nobel Prize winner

Carlos Rubbia to propose the development of ADS. Still, the ADS is a machine based on the fission reactor, which means that the necessity remains unchanged to remove decay heat reliably to protect a nested system of barriers against the release of highly radioactive fission products.

ADS is one of the potential solutions to close the fuel cycle, as outlined in section 7.2.4. An advanced reprocessing based on partitioning is of course needed, too.

A spallation target cooled by molten lead-bismuth was successfully tested in the MEGAPIE project carried out at PSI in Switzerland. The target had a beam power of 1 MW and was operated for approximately 3 months. For a commercial ADS, the beam power has to be up-scaled by a factor of 10.

The most mature project is MYRRHA, a Multipurpose Hybrid Research Reactor for High-tech Applications, proposed by the research centre in Mol, Belgium. It is planned as a 57 MW thermal, subcritical assembly driven by a proton beam of 1.5 MW. Belgium agreed to contribute up to 40 % of the funds needed, which enables a start of the construction in 2015 and a planned commissioning in 2023. The organizers are still in search for funding partners. A small-scale preliminary test was performed in 2010.

7.2.6 Summary

Energy generation by nuclear fission is a vital field of industrial activity as well as an area of multiple diversified research and development efforts worldwide. Political decisions, phase-out decisions in some countries, are confronted with new building projects in others, and numerous, quite promising mid- and long-term development programmes are on going. The state-of-the-art is characterized by generation III systems which were developed with the goal to abandon the necessity for measures of external emergency response by deterministically excluding either the core damage or the release of large amounts of radioactive substances in case of such an event, whereas the core damage frequency was drastically reduced by strengthening the protection and emergency systems of the reactor. In the end, newly built projects offer a very high degree of safety, but it is not possible for fundamental reasons to eliminate a residual risk completely. However, major accidents such as those of Chernobyl and Fukushima, happened on plants of generation II that were not sufficiently upgraded with regard to the current knowledge on severe accidents and external events initiating an accident. In Chernobyl and Fukushima, it was therefore not the corresponding current state-of-the-art that failed, but the way the state-of-the-art was taken into account by the utilities and the regulator.

Nuclear technology offers solutions that can provide an outstanding gain in sustainability, both at the front and the back end of the fuel cycle. Generation IV systems are not just subjects of purely theoretical considerations – the general feasibility of most of the reactor concepts has already been experimentally proven in considerable scales, which are sometimes very close to installed electrical power rates interesting from the point of view of a commercial use. Still, the development has to continue, mainly to solve open issues concerning safety and reliability.

7.3 Wind

7.3.1 Wind energy development and outlook in the European Union

The expansion of the wind energy use for power generation in the European Union has a 25 year old history. In 1990 the installed wind capacity was app. 500 MW. This number grew steadily, and by the year 2000 reached 13,000 MW which amounted to 0.7% of the total generation in the EU. This was still an insignificant share, but has increased to 6.3% by the end of 2011. With double digit growth rates, outstanding high dynamics have been observed since the middle of the last decade. With 10,500 MW of new wind capacity installed in the European (EU27) market in 2009 it reached its highest historical annual level. Nevertheless, due to the economic crisis new installations have decreased to 9,648 MW and 9,618 MW in the 2010 and 2011 respectively. Within Europe five countries (Germany (20%), the UK (12%), France (9%), Romania (8%) and Italy (8%)) accounted for app. 60% of the region's deliveries. As a regional market Europe saw a 2% drop in market share, down to 25% in 2011. With a total installed wind fleet capacity of 94,000 MW by the end of 2011, the EU has app. 40% of the current worldwide installed fleet of 238,000 MW [EWEA 2012], [GWEC 2012].

Despite this recent stagnation, wind power generation has developed as a profound part of the European generation mix. Supported by the long term oriented European Energy Policy („20-20-20 targets") we project wind energy to be an essential contributor to the environmentally sustainable future energy supply. Emerging Energy Research projects that wind energy additions will increase as much as 16,000 MW by 2020 [EER 2011]. The Global Wind Energy Council [GWEC 2010] projects a European wind power fleet capacity of 234,000 – 515,000 MW by 2030. In addition, the International Energy Agency projects (IEA) projects a significant increase of the wind role in its contribution to the European energy mix. Depending on the scenario, the share of wind power in the generation mix increases by 2035 up to 19 % (NPS scenario) and 24% (450 scenario) [IEA 2011]. The resulting capacity amounts to 307,000 MW in the NPS scenario, and 370,000 MW in the 450 scenario.

Beyond the ongoing development of the new onshore green-fields with good wind conditions we expect additional two growth trends

- Wind use in regions with poor wind conditions supported by partial replacement of the wind plants of the first generation (Repowering)

- Wind use of Offshore – plants, preferred in shallow waters with excellent wind speed conditions and high load factors

7.3.1.1 Regions with poor wind conditions, repowering

Opening up of regions with poor wind conditions is one of the key components of realization of European targets for the strong extension of renewable energy use.

Measures like the increase of the hub height and reduction of the specific power per rotor surface will enable a significant improvement of the energy yield in regions with relative low wind speeds. The reason is due to both the increase of the average wind speed due to the height, and a decreased required wind speed by keeping a constant generator capacity and increasing rotor surface resulting in higher load factors. Based on an example of a 2 MW wind plant located in Bavaria in Germany we demonstrate that by the use of commonly available state of the art"- wind technology with hub height of 116 m and in combination with a rotor of 93m diameter an 80 % increase of the energy generated by the plant is possible, see figure 38 [IWES 2011]. Such a large improvement delivers a motivation for the replacement of older units by more modern ones, even in regions with weak wind conditions.

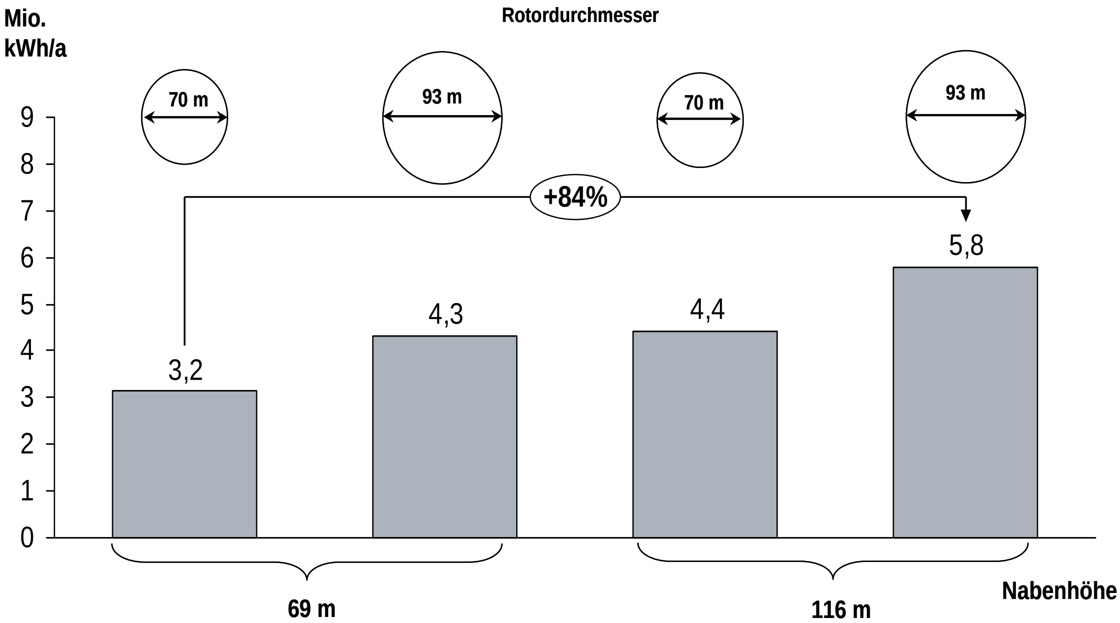


Figure 38: Additional generation of a 2 MW wind plant in South Germany due to the increase of the hub height and rotor diameter [IWES 2011]

7.3.1.2 Offshore wind

Most of the recently published studies include scenarios which project high dynamics for future offshore wind power plants additions. The main reason can be seen in the high load factors in the range of 40%, which can be achieved on the sea and result in the high energy contribution of offshore wind farms. Additionally, the steady wind conditions on the sea and reliable weather prognostication comply with system flexibility requirements.

The development of 2009 and 2010, in which 50% more capacity has been added each year confirms this outlook. Nevertheless, during the year 2011 866 MW have been installed, almost the same capacity as in the previous year. The main reasons for this holdup are delays in the realization of planned 3 GW of 10 offshore projects in Germany, which originally had to be commissioned by 2012.

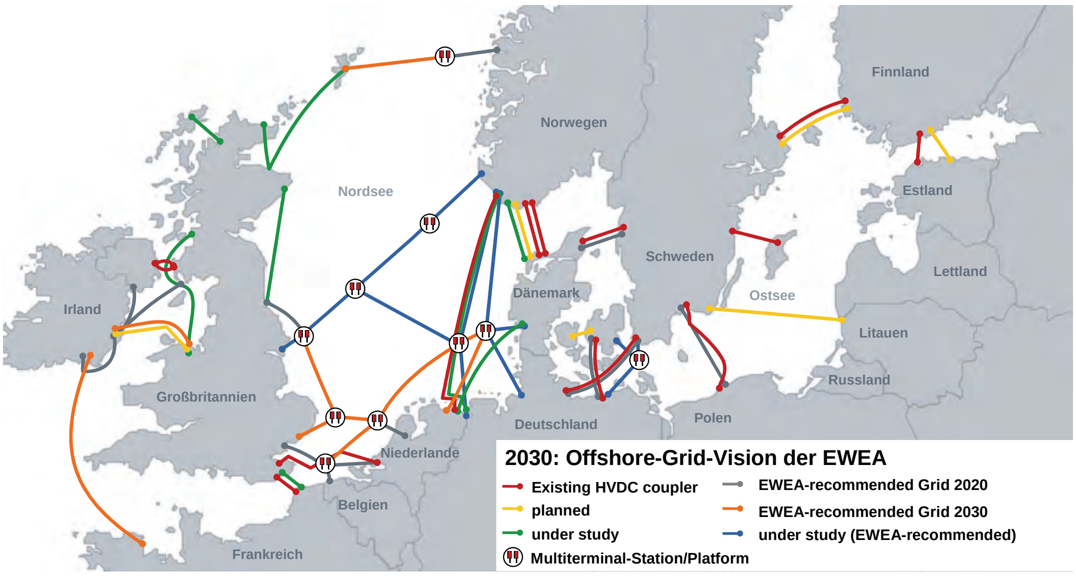
At the end of 2011 the European offshore fleet grew to 3,813 MW [EWEA 2011]. The average offshore wind farm size in 2011 was almost 200MW, up 29% from the previous year. Average water depth in 2011 reached 22.8m, substantially more than the previous year. Average distance to shore decreased to 23 km in 2011 from 27.1km the previous year. However, the distance of wind farms currently under construction is 33.2km. A distance from the shore in the range of 40 km is not unusual, especially in Germany. Currently nine new projects with a total capacity of almost 2,400 MW are under construction and preparatory works for a further nine projects sites have begun. Despite postponements in the realization of the projects, Europe plays, in comparison to other world-regions, the leading position and pioneering role in the development and implementation of this seminal technology.

Due to the exceptional usable offshore wind, supported by ambitious expansion plans, this technology brings the long term, bright, prospect potentials to the North- and Baltic seas. Successful project development and realization, as well as implementation of proven technology will be a deciding factor about the speed of further wind offshore additions. In the first phase of offshore-wind expansion the regions combining high wind speeds (> 8 m/s), short shore-distance (< 40km) and shallow water depth (< 40 m) will play a key role. Most of the 74,000 MW projected by 2025 will be constructed on the coasts of United Kingdom, Germany, Denmark, Sweden, Netherlands and Belgium [EER 2011]

Nevertheless, these long terms, bright prospects face some short term challenges which have to be successfully solved. One of the most important issues needing improvement is the high project costs. The total system prices have tripled over the last decade, and have reached 3000-4000 €/kW. Aggressive cost reduction measures are necessary to push offshore wind generation costs down to competitive levels. Those measures should be going beyond the turbine cost alone, which amount to app. 1/3 of the total project costs. They should address project financing costs, foundations, O&M part and even costs for power conversion and transport to the onshore grid. Furthermore, a smooth integration of the wind farms with transport infrastructure off- and onshore requires accelerated and coordinated actions on the regulatory and industry side, as well as an improvement of societal acceptance.

7.3.2 Grid- Integration of offshore wind plants

One of the main challenges concerning system operation with significant contribution from wind generation is the balance between production and consumption in the presence of wind variability. Also the potential for large simultaneous tripping of wind power, which may result from network voltage dips associated with correctly cleared network faults need to be properly managed. The improvement of weather forecasting and implementation of flexible thermal plants to cover the residual load are promising mitigations, which are perceived to address these challenges. Moreover, further capacity increase and strengthening of the European network is anticipated to be needed in order to integrate large and quickly increasing amounts of wind capacities. Therefore, the accelerated construction of the offshore grid and a further expansion of the onshore grid are of high importance. The European Wind Energy Association (EWEA) has developed a concept of transnational European super-grids, which is based on the currently planned offshore wind expansion plans; see figure 39 [EWEA 2010]. By 2030, the existing transmission lines (in red: 7,350 MW) and the binding planned additional capacities (yellow: 4,950 MW) should be extended by those, which are in a feasibility stage (green: 10,400 MW, blue: 9,600 MW). Related decisions of the European Energy Commission and ENTSO-E are expected during 2012. In addition, EWEA recommends by 2020 an additional 7,100 MW (grey) and by 2030 a further extension by 11,000 MW. The main idea of the establishment of this new grid is to address the large scale electricity exchange between regional centers of power generation and demand. The identification and opening up of the related synergies has the potential to develop and establish the offshore wind utilization as one of the profound cornerstones of the sustainable and reliable energy supply in this century.



Quelle: European Wind Energy Association (EWEA) 2009/2010, Siemens

Figure 39: Concept of the European offshore – super-grid in North Europe

The building up of an extensive offshore grid infrastructure and the corresponding appropriate extension of the onshore grid develop the key priorities of the European energy policy. Some essential technical points are still under discussion, i.e. question, if using of the existing 380 kV transmission technology will be sufficient to transmit high capacities from the coast to demand centers. In the long term questions of preferred technologies have to be clarified. I.e. if high voltage DC lines (+800 kV, 6 GW) or ultra-high voltage AC (1000kV, 8 GW double circuit lines) provide more advantages in the context of optimal European grid extension. Additional important issue is the securing of adequate reactive power in the grid in regions with high shares of renewable energy supply. Especially in the areas with quickly rising wind feed in, and with simultaneously decreasing shares of conventional thermal power plants the demand for reactive power could increase fairly quickly. In this regard an additional reactive power demand challenge results in regions with high photovoltaic grid feed in

7.3.3 Innovations and trends

Over a relatively short life time of the modern wind technology many technology trends have already emerged. The technological progress can be predominately observed based on the continuous increase of the power output from single wind mills. In Germany, one of the leading European markets with the longest history of wind application, the average size of new installed turbines has increased from 180 kW in 1990 to 2 MW in 2010, see figure 40.

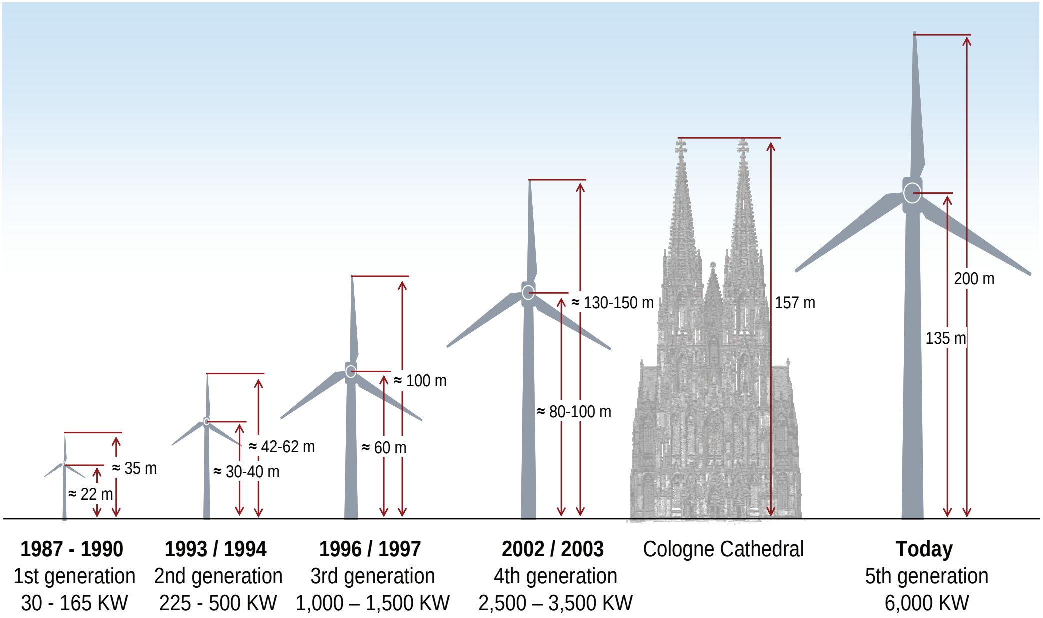


Figure 40: Development of the size of the wind power plants

The trend to higher turbine sizes, especially in emerging offshore farms accelerates. The manufacturers like Enercon, Repower, Areva, BARD, or Siemens currently offer turbines with a capacity of 5 MW or larger. The most recent technology achievements have been demonstrated by the SWT-6.0 turbine from Siemens, which has been introduced in November 2011. This new offshore wind turbine redefines the wind industry standards for leanness and robustness and demonstrates multiple innovation steps, which are helpful especially in offshore applications. Based on direct drive technology, which is one of the most recent break-through technologies, the 6.0 MW turbine has 50% fewer moving parts than comparable geared machines, and a tower head mass of less than 350 tons, figure 34. The combination of robustness and low weight significantly reduces infrastructure, installation and servicing costs, and boosts lifetime energy output. The turbine is equipped with pitch regulation with variable speed, which constantly manages its own operating load helping it remain within its design criteria irrespective of the weather conditions. Its advanced diagnostics system provides comprehensive real-time performance data and service requirements and is designed to keep track of lifetime use and its overall asset condition.

It is assumed, that in the near future plants in a double digit MW size range will be introduced to the market

Figure 41: Gearless Siemens SWT-6.0 wind plant. Comparison of the 154 m rotor with the Air-bus A 380

The European wind fleet is currently dominated by geared turbine, 1-2 generation technology equipped with asynchronous generators. This reliable technology has proven it value in plants with capacity less than 1 MW. With the progressing application of bigger turbine sizes limits of geared technology have become more and more visible. Continuously increasing weight and technical failures with components rotating at 1200 -1800 rpm have driven the development of gearless technology. Significant material and weight savings, as well as implementation of synchronous generator with low rotation speed of 12-30 rpm enable heightening of towers and following of increase of turbine capacities. Those measures lead to minimization of internal losses and to advances of the plant maintainability. Simultaneously, due to the advancement in the development of materials, the enhanced elasticity and aerodynamics allow a construction of longer and more reliable blades. The progress in the automation of manufacturing processes, and material- and weight savings impact the improvement of reliability and finally help to improve the operation economics.

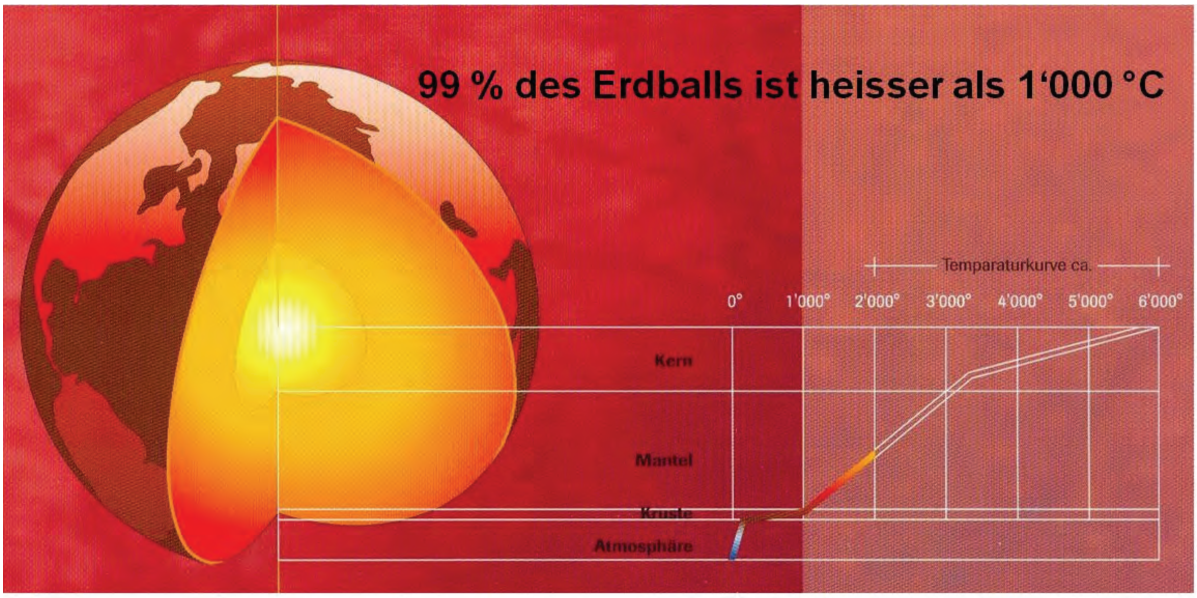
7.4 Geothermal

7.4.1 Introduction

Geothermal energy is an indigenous, environmentally friendly and virtually inexhaustible, renewable energy which can be used in every country on earth. 99% of the Earth's mass is hotter than 1000 °C, 0.1% colder than 100 °C. Additionally, a radioactive decay of uranium, thorium and other fission products is active within the earth and constantly generates new heat. Some of this heat is radiated into space. These losses are marginal compared to the energy content of the Earth's mass and to the energy that is constantly generated. A model calculation has shown that the earth has cooled only about 300 - 350 °C over the last 3 billion years.

If the entire global energy consumption was generated by geothermal energy today, it would only be a fraction of the heat generated in the earth's interior or the daily energy radiated into space. Knowing this, we can say that terrestrial heat is a virtually inexhaustible energy source, available 24 hours a day, 365 days a year.

With today's investments, one can only use geothermal energy in the Earth's crust, i.e. in the sediment and the solid rock (bedrock). If one imagines the earth as a bird's egg, then the egg-shell is equivalent to the Earth's crust, the liquid part of the egg to the liquid portion (magma) of the earth. This crust is between 20 and 65 km thick, under the oceans 5 to 6 km. The average thermal gradient is 2.5 - 4 °C per hundred meters depth, i.e. in 1000 meters below the surface there are temperatures of 25 to 40 °C and at 5000 meters 125 to 200 °C.



Quelle: M. Häring

Figure 42: Temperature profile of the Earth

The thermal gradient depends on various factors. The gradient is smaller in former glaciers of the last ice age, as the earth was covered by glaciers for a long time and has cooled. Moreover, the gradient is also smaller – less than 1 °C per 100 meters – in areas where the deep bedrock sank into the earth and the resulting depressions were filled by sediments. On the other hand, there are also areas where the gradient can reach a multiple of the average, for example, in volcanic areas like Iceland, Italy, Indonesia, etc. and at the breaches of plate tectonics, e.g. the Great Rift Valley, San Andreas Fault in California, the Upper Rhine Cut or where the crust is thinner.

7.4.2 Energy potential

The energy potential of the entire Earth's mass is immense. However, only a fraction of this energy can be used, as the access is difficult in the oceans and as a low thermal gradient makes the exploration economically unprofitable in other places. But the utilisable potential is still a multiple of today's energy consumption.

7.4.3 Geothermal energy use

Geothermal energy – in the form of hot springs – has been used by our ancestors since primitive times. By 1740, the thermometer was invented. This made it possible to discover the temperature rise in a mine in Belfort (France), the deeper one descended into the earth. The hot springs at Larderello (Italy) were used for industrial purposes already at the beginning of the industrial age. At first it was process steam for the extraction of boric acid. Later, very hot steam was accessed with deeper holes, making it possible in 1904 to install the first steam turbine generator for the production of electricity. Today, the installed electrical capacity of the geothermal power plants at Larderello is 545 MW. On a global scale, there are about 11 GW electric power and 50 GW heat. This is roughly equivalent to the output of 11 nuclear power plants. To date, geothermal energy is used almost exclusively with thermal sources (aquifers).

Figure 43: Geothermal pioneers (Lardello, Italy1903)

7.4.4 Geothermal energy systems

Today, one can distinguish between 4 different systems.

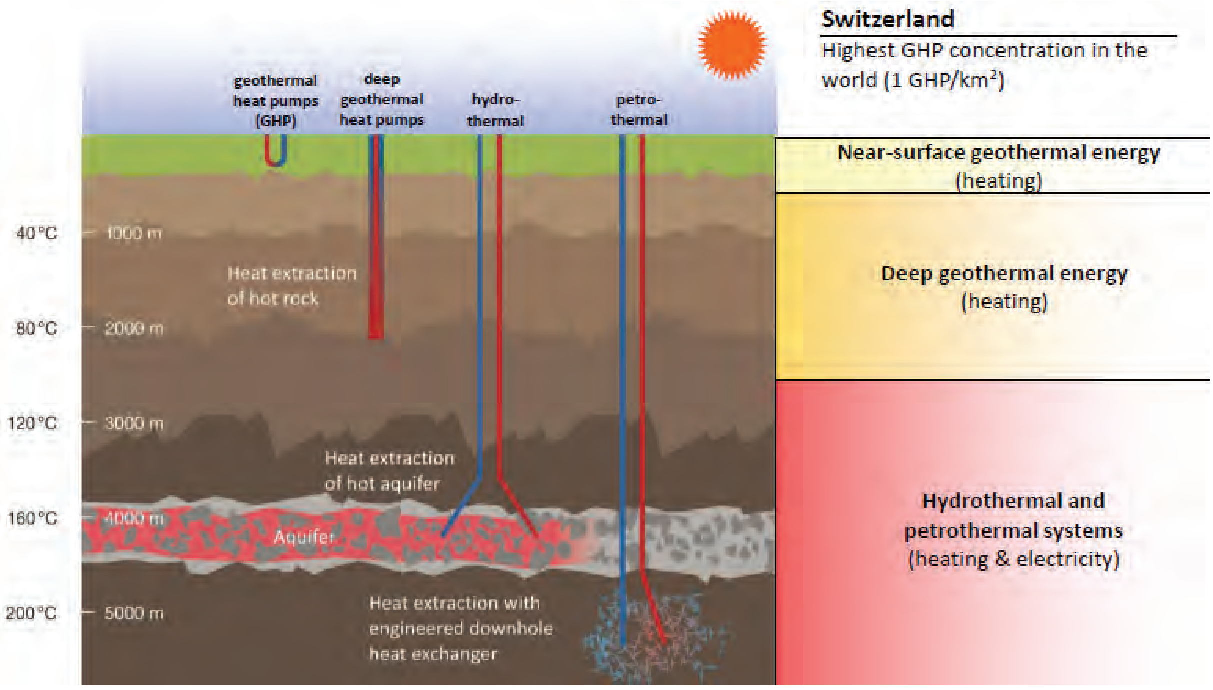


Figure 44: Geothermal energy use

7.4.4.1 Surface geothermal energy

The depth range between 150 and 600 meters is mainly used for home heating or cooling with heat pumps. Double tubes are inserted into the drillings and filled with water. The heated water (10 - 25 °C) is circulated and fed into a heat pump. This raises the water temperature of a secondary circulation to the necessary heating temperature. The electrical energy needed for this is about 20 - 25% of the produced heat energy. This is a real contribution to the substitution of fossil fuels.

Deeper geothermal energy for heating purposes goes down to 2000 meters. This kind of thermal energy can be directly fed into heating circuits without the use of a heat pump. From an economic perspective, this technology is particularly interesting for large housing estates.

7.4.4.2 Hydrothermal systems

Hydrothermal systems make use of hot waters (aquifers) in deep, water-bearing layers. These Layers, interesting for the utilisation of heat and for the generation of electricity, can be located in depths between 2500 and 4000 meters (figure 44).

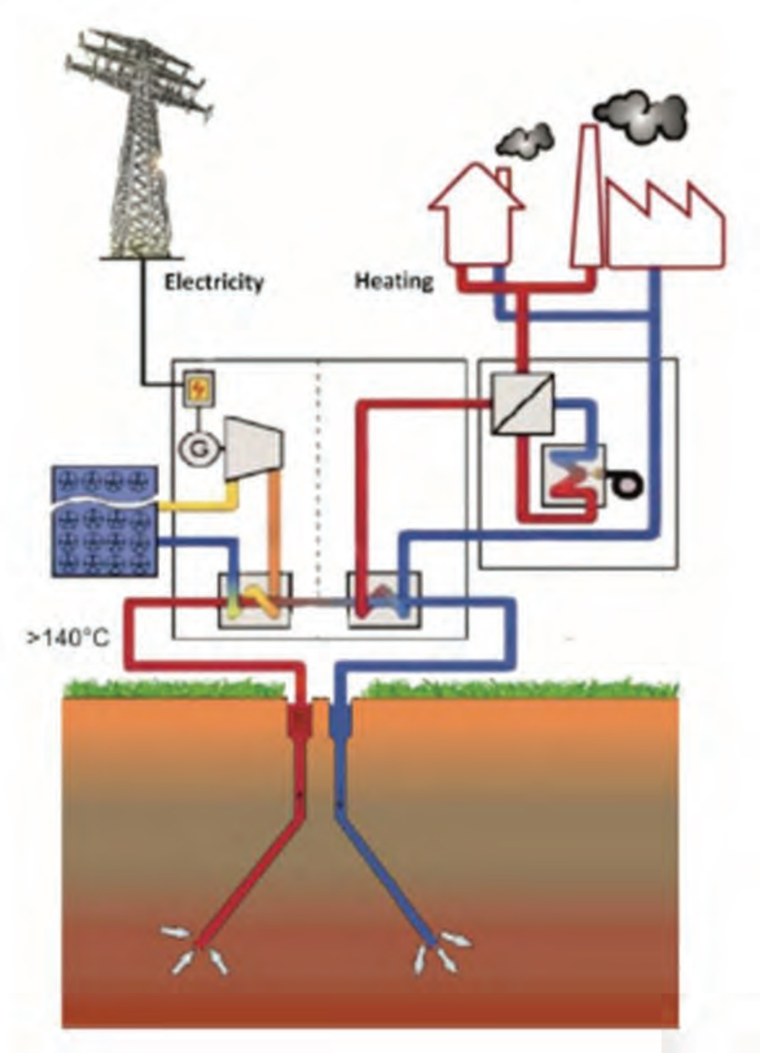


Figure 45: Geothermal Power Plant (Heinze et al. (2003)

Such aquifers with temperatures between 100 and 150 °C are mainly found in Jura layers and here especially in zones with geological fault systems, or in zones with volcanic or tectonic activity.

These hot waters are pumped by means of a downhole pump to the earth's surface or pumped to the power plant and normally conducted via a heat exchanger. The secondary circuit of the heat exchanger then feeds a steam turbine to generate electricity and/or thermal power. The hot water is then again injected into the aquifer. This closed circuit prevents a possible contamination of the Earth's surface. The drilling success of such aquifers is relatively limited and the exploration has its risks.

7.4.4.3 Petro thermal Systems

In these systems, at least 2 holes are drilled into the basement rock (granite and gneiss) down to 5000 meters. There, the temperatures are between 150 and 200 °C on average. Water or acids are then pressed into the rock with high pressure. This opens up naturally occurring rock cracks. The very high mountain pressure causes the sides of the cracks to be shifted against each other (fracturing). This results in transmissive places that can be used as a natural heat exchanger. The fracturing produces small earthquakes, usually micro earthquakes, which are hardly noticeable. This method has been used in gas exploration for some time. Water is forced into one of the above-described holes (injection well) into the heat exchanger and the heated water is pumped to the surface through the second bore (production well). The heated water is used in the same way as in a hydrothermal system.

Such a heat exchanger with an edge length of 1 km, i.e. a cube of 1 km^3 at a temperature of 200 °C may produce 10 MW of electric power for 20 years. A cube with an edge length of about 3.1 km, i.e. a capacity of 30 km^3 supplies a power of 300 MW – the power for about 300000 people – 24 hours a day, 365 days a year. After this time, the temperature of the heat exchanger has dropped by about 20 °C. This reduces the system’s efficiency.

7.4.4.4 Use period of geothermal systems

Sediments and rocks are like heat insulators (construction). Accordingly, the flow velocity is very small and only reaches a few millimetres per year. I.e. if the rock was cooled by artificial heat extraction for heat or electricity production purposes, it takes much longer to reach the original temperature again.

In the case of surface geothermal energy, only a low percentage of the heat is extracted or only as much heat as can be continually regenerated. In this way, the source can be used for several decades at least. The heat usage can be improved by injecting heat generated by solar collectors or by air conditionings into the bore. The excess heat is returned to the bore.

Depending on the size and the capacity of the water-filled underground system, hydrothermal systems can be used for various lengths of time. Today, one assumes a life span of 30 years.

An economic use of petro thermal systems with heat exchangers is assumed to be possible for over 20 years. This depends on how much the rock is cooled down by the heat absorption and which minimal efficiency is expected. One could imagine that if the lower temperature limit of the existing wells is reached, one could drill down by a further 1000 m and realize a new heat exchanger at that depth. This would be much cheaper than a new unit, since the original bore and the plant can still be used.

7.4.5 Exploitability of various geothermal systems

Surface geothermal energy can be employed to generate heat (and cold) using heat pumps practically all over the world. The efficiency depends essentially on the thermal gradient. In Central Europe, one can expect a factor of 1:4 to 1:5, i.e. to produce heat energy of 10 kWh, 2.5 or 2 kWh of electrical energy are required.

Hydrothermal systems are quite difficult to locate, except in cases where hot water escapes or hot springs exit the surface (Larderello in Italy). As described above, certain anomalies and geological fault systems enable one to assume the presence of water-carrying systems. However, certainty can only be obtained by drilling. I.e. the exploration of hydrothermal systems is associated with some risks.

Basically, petro thermal systems can be used worldwide. Because of the higher temperatures needed, these systems are mainly suited for electricity production. To date, there are initial pilot or research projects (Soulz sur Forret). A considerable research effort is still needed to make such a system widely useable. If this breakthrough takes place – which no doubt will happen one day – this technology can substantially contribute to the substitution of fossil electricity production.

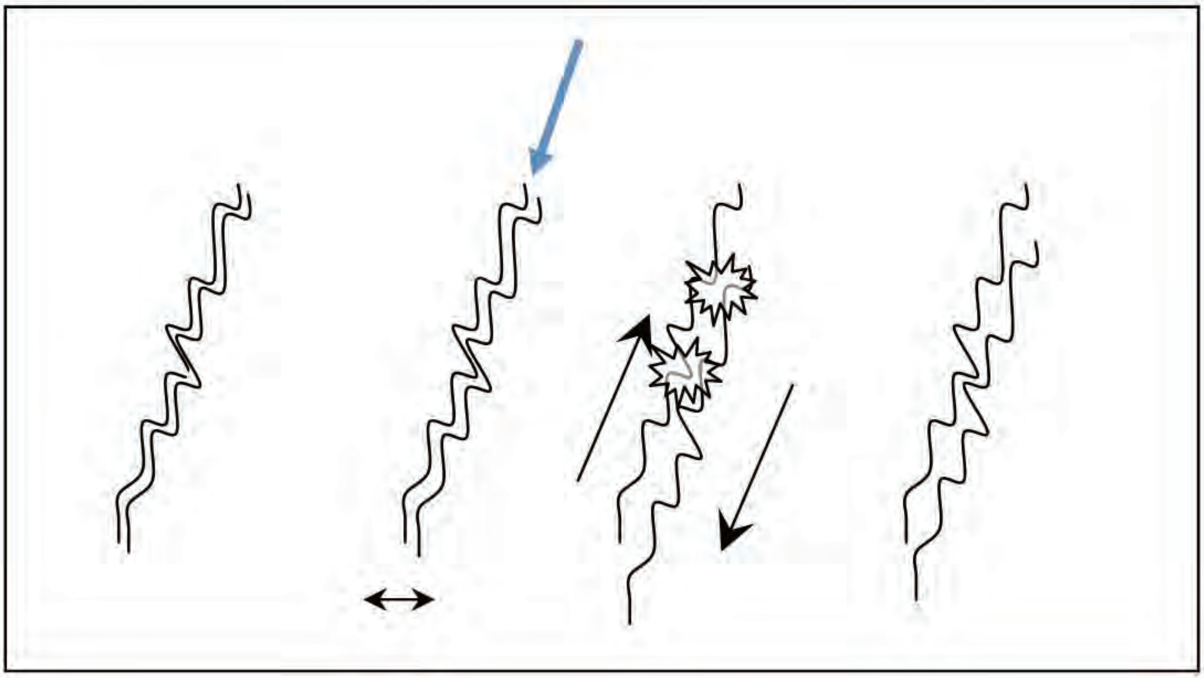


Figure 46: Microseism

7.4.6 Exploration

The drilling technology for geothermal probes has achieved a high level. Today, a 250 m deep bore for a detached house can be realised within a working day.

For deeper drillings, one still uses a drill bit with traditional drilling rods. As the drilling costs of a geothermal power plant amount to about 70% of the total costs, new processes are needed. The ETH Zurich is researching a new technology based on a flame technology that should enable higher drilling rates without the need for drilling rods with all their complicated handling.

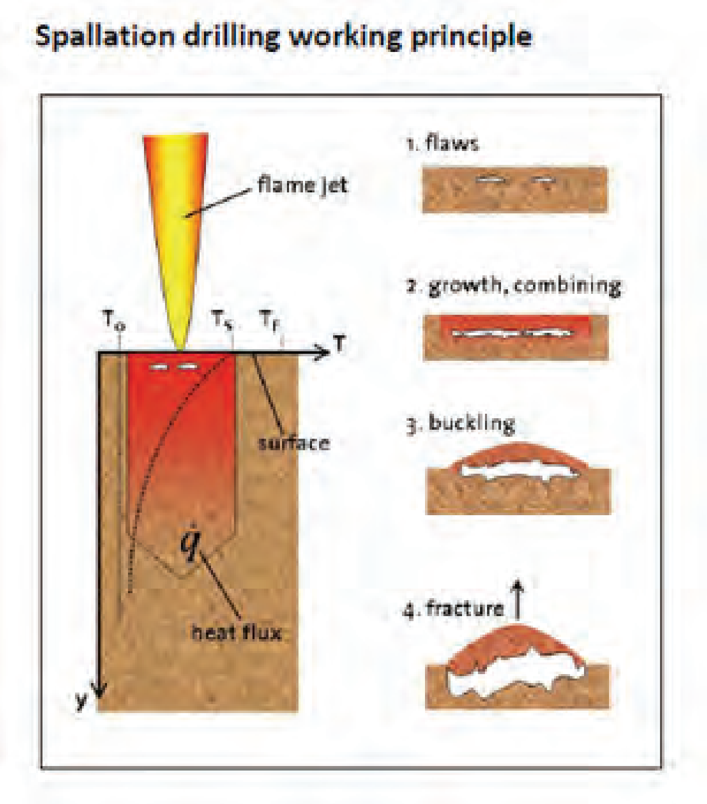


Figure 47: Drilling

The fracturing used for the realisation of the underground heat exchanger for petro thermal systems has been used in gas exploration for a long time. The micro earthquakes generated in uninhabited areas are no problem, as is the case in most previous gas discovery places. The advantage of petro thermal systems is the fact that energy (electricity and heat) can be produced in the immediate vicinity of the consumer. Micro fracturing earthquakes may cause fears in the affected population which may put the whole project into question (Basel).

Here, solutions must be found that can help to keep such micro quakes under control and make them acceptable to the population.

7.4.7 Environmental aspects

During drilling, the drilling mud may contain Sulphates, Sodium, Chlorine, Boron etc. and has to be disposed of as hazardous waste. Additionally, it is also possible that gases such as methane, ammonia, etc. are released. But these gas emissions have been under control for quite some time. During the operation of a geothermal power plant emissions only in connection with the secondary cooling circuit of the steam turbine can be expected (steam and possible fan noise). The footprint of the aboveground part of the power plant is comparable to that of a gas power plant.

7.4.8 Production costs

Today, one expects costs of 0.13 – 0.25 € for a geothermal power plant with 1 kWh electric power. As progress is made in research and development, future costs will be considerably lower.

7.5 Photovoltaics

7.5.1 Introduction

The energy of solar radiation can be used directly in the form of heat or converted to electrical energy using solar cells. It is believed that solar radiation has a constant value since ancient times. On the edge of the Earth's atmosphere it is 1,367 kW/m² (solar constant). A part of this radiation is reflected from the atmosphere, a part absorbed and converted into heat and most of the radiation reaches the earth's surface. The intensity of the radiation does not only depend on the time of day, but also on meteorological conditions as well as altitude and latitude.

7.5.2 Potential of solar energy

The sun is the largest energy source that can easily be used on Earth. The annual solar energy quantity that reaches the earth is 1.5 x 10^{15} MWh. This represents more than 10,000 times the total world energy consumption of humanity in 2010.

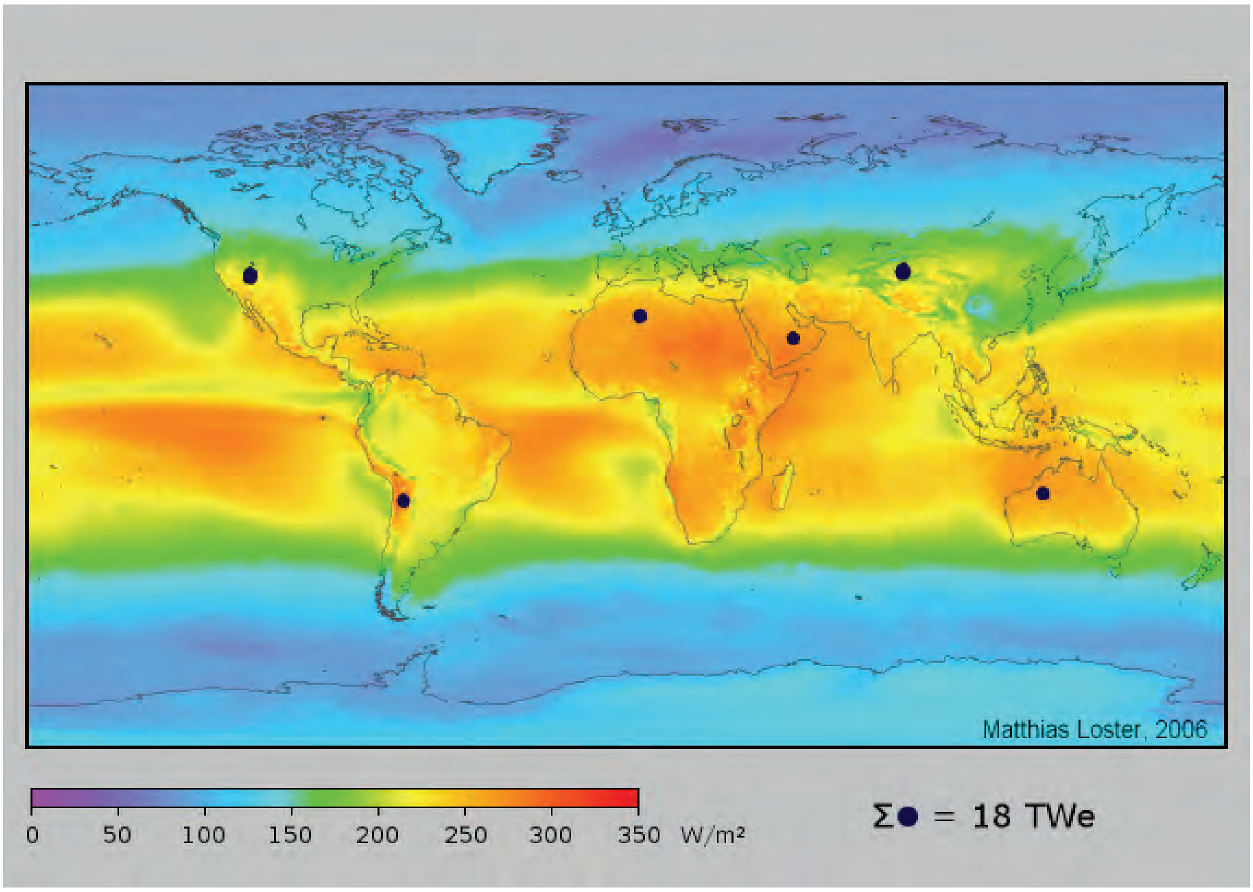


Figure 48: Average solar irradiance

In order to optimally convert solar radiation to electric energy with the help of photovoltaic cells, the radiation should impinge on the cell at a right angle and the cell temperature should be around 5 °C. This is not realistic for most applications. Depending on the time of day and season and on altitude and latitude, the irradiated solar energy is about 1000 W/m² in central Europe and 2500 W/m² in the Sahara Desert. If the current efficiency of industrially manufactured photovoltaic modules is considered to be 14-20 %, an area of around 6 – 8 m² is needed to install a power of 1 kW. With this power of 1 kW one can e.g. produce an energy quantity of approx. 800 kWh per year in Germany. I.e. the time in which the solar radiation is sufficiently strong for electricity production with solar cells is 800 hours. In northern Italy, this time is about 1100 hours. For comparison purposes: A year has 8760 hours.

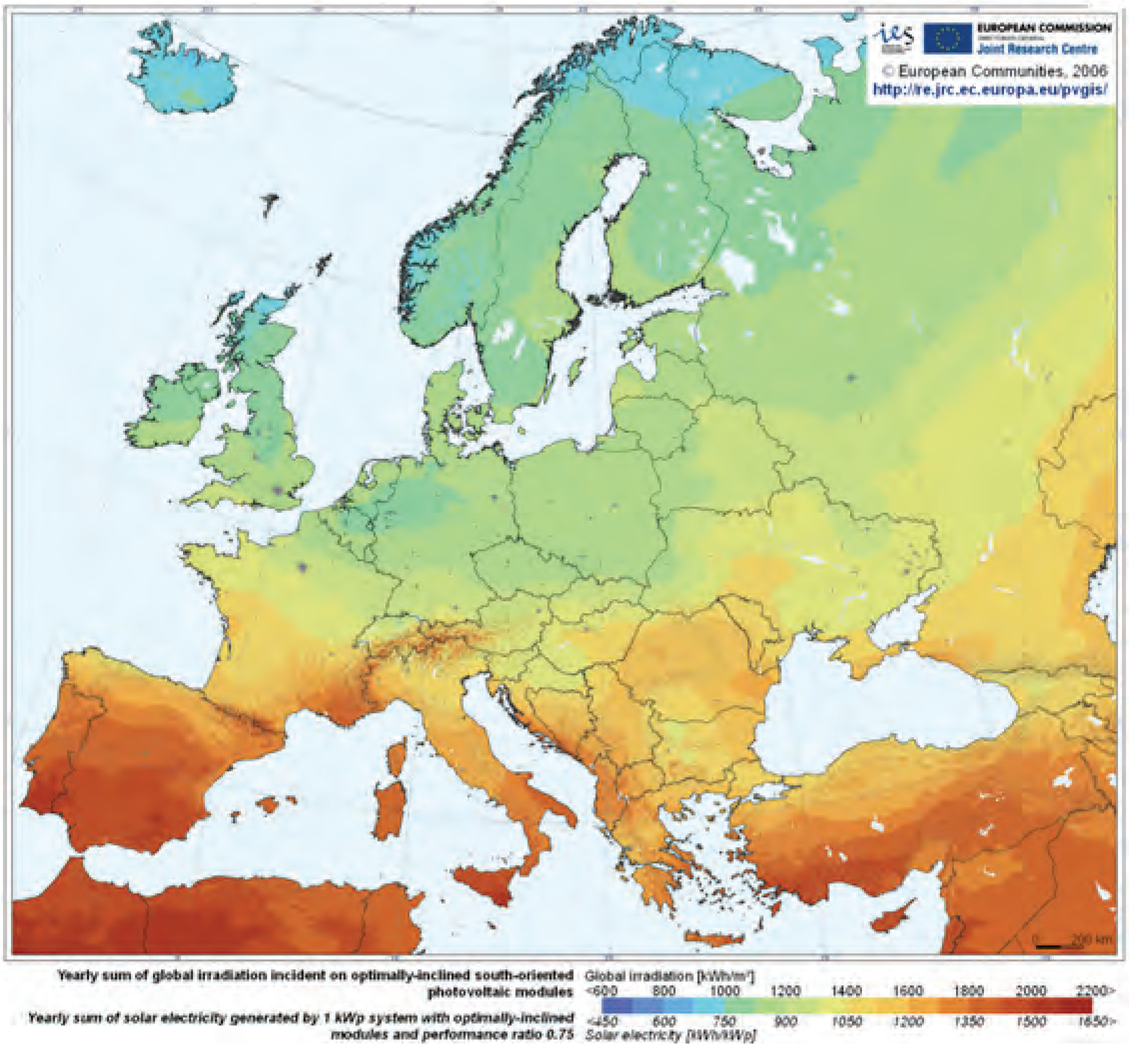


Figure 49: Solar Electricity Potential in European Countries

7.5.3 The photoelectric effect

The photoelectric effect was discovered in 1839 by French physicist Alexandre Edmonde Becquerel. Albert Einstein was able to demonstrate the photoelectric effect in 1905 physically and was honored for this with the Nobel Prize. In 1954, electricity was generated from light with silicon cells for the first time. The efficiency was 4-6%. Today, one can achieve over 30% under laboratory conditions with highly concentrated light. Most current photovoltaic modules (with mono-and polycrystalline silicon cells) have an average efficiency of about 16%.

7.5.4 How solar cells work

A solar cell is an electronic component consisting of a semiconductor which converts short-wave radiation energy (e.g. solar energy) into electrical energy based on the photoelectric effect. I.e. it is constructed as a photodiode which is operated as a current source. With the supplied radiation energy (electromagnetic radiation) free charge carriers are generated. These charge carriers need an electric field to generate an electric current. A targeted doping of the material – a p-n-transition (solid state technology) – creates this electrical field.

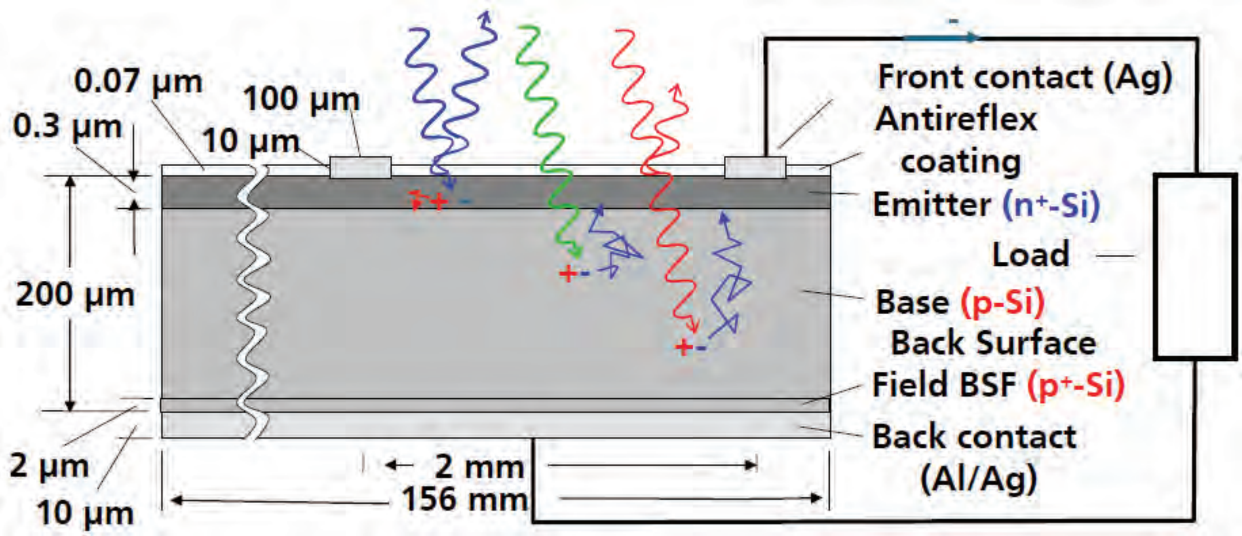


Figure 50: The Standard c-Si Solar Cell Structure (Fraunhofer ISE)

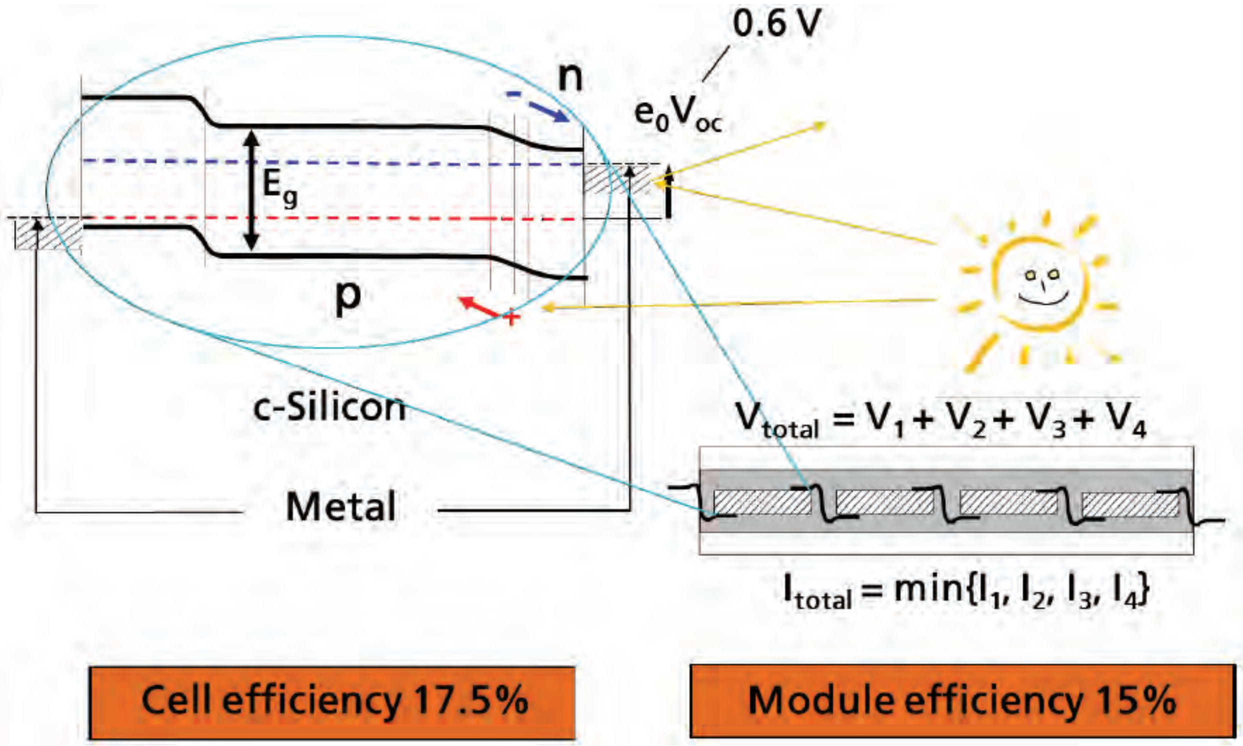


Figure 51: Crystalline Silicon Cell and Module (Fraunhofer ISE)

7.5.5 Solar Cell Types

7.5.5.1 Silicon cells

Quartz sand is used to produce raw silicon in a blast furnace. Via a multi-stage, energy-intensive process extremely pure silicon is produced. Various methods are used to melt this ultrapure silicon in quadratic or round crucibles by induction heating to make corresponding silicon crystal ingots. It is also possible to apply the silicon onto a carrier material in the required thickness in a continuous casting process.

Thick film: Here, the cylindrical Silicon ingots are cut with wire saws into discs (so-called wafers). The thickness of these discs is 0.18 – 0.28 mm.

- - Industrially manufactured monocrystalline Silicon cells (c-Si) reach an efficiency of 20% in large-scale applications. The technology is very mature. Nevertheless, manufacturing requires a lot of energy which is negative concerning the energy payback time. This technology is the second most current one, the market share is about 35%.
- - Polycrystalline silicon cells (poly-Si) have a good cost/performance ratio, a short energy payback time and reach an efficiency of 16%. They are the most sold solar cell with a market share of around 50%.

Thin film: The material of thin film cells (amorphous cells) is deposited on a substrate. The physical properties and efficiencies differ from traditional solar cells. Amorphous silicon is by far the most widely used material in thin film cells. The efficiency is around 5 – 7%.

In the "Si Wire Array" technology, very thin silicon wires are mounted on the surface. This makes the surface flexible. Moreover, only about 1% of silicon is needed compared to conventional cells. (Laboratory stage)

Tandem solar cells are multiple layer solar cells, usually in combination with polycrystalline and amorphous cells.

7.5.5.2 Solid state solar cells

GaAs cells (Gallium Arsenide) are very efficient (over 40% in the laboratory). They are very expensive and are primarily used in aeronautics.

CdTe cells (Cadmium telluride) can be manufactured as thin film cells reasonably cheaply. They reach a module efficiency of 10%. The durability is not yet known.

CIS cells (Copper Indium (Di)selenide). Used in thin film cells with a high efficiency of over 17%.

The materials of solid state cells are usually poisonous and difficult to recycle.

Organic solar cells and the Grätzel cell (organic dyes) have a very limited durability today.

7.5.6 Availability of basic solar cell materials

Silicon is the basic material of the largest share of all solar cells produced today. It is the second most common element and occurs practically all over the world.

The more exotic materials for the production of special cells, such as Indium, Selenium, Gallium, and Tellurium are relatively rare and are also used in the production of LEDs (light bulb replacement) or liquid crystals. Due to the massive increase in production in these areas and the difficult recycling of these materials, some of these materials are likely not to be available any longer in the foreseeable future.

7.5.7 Availability of photovoltaics

The possibility of generating solar electricity can be calculated for each site, based on the astronomical sunshine duration and the daily sequence, each related to the respective degree of latitude. It is also affected by the meteorological conditions and, in rare cases, by the clouding of the atmosphere by volcanic ash eruptions.

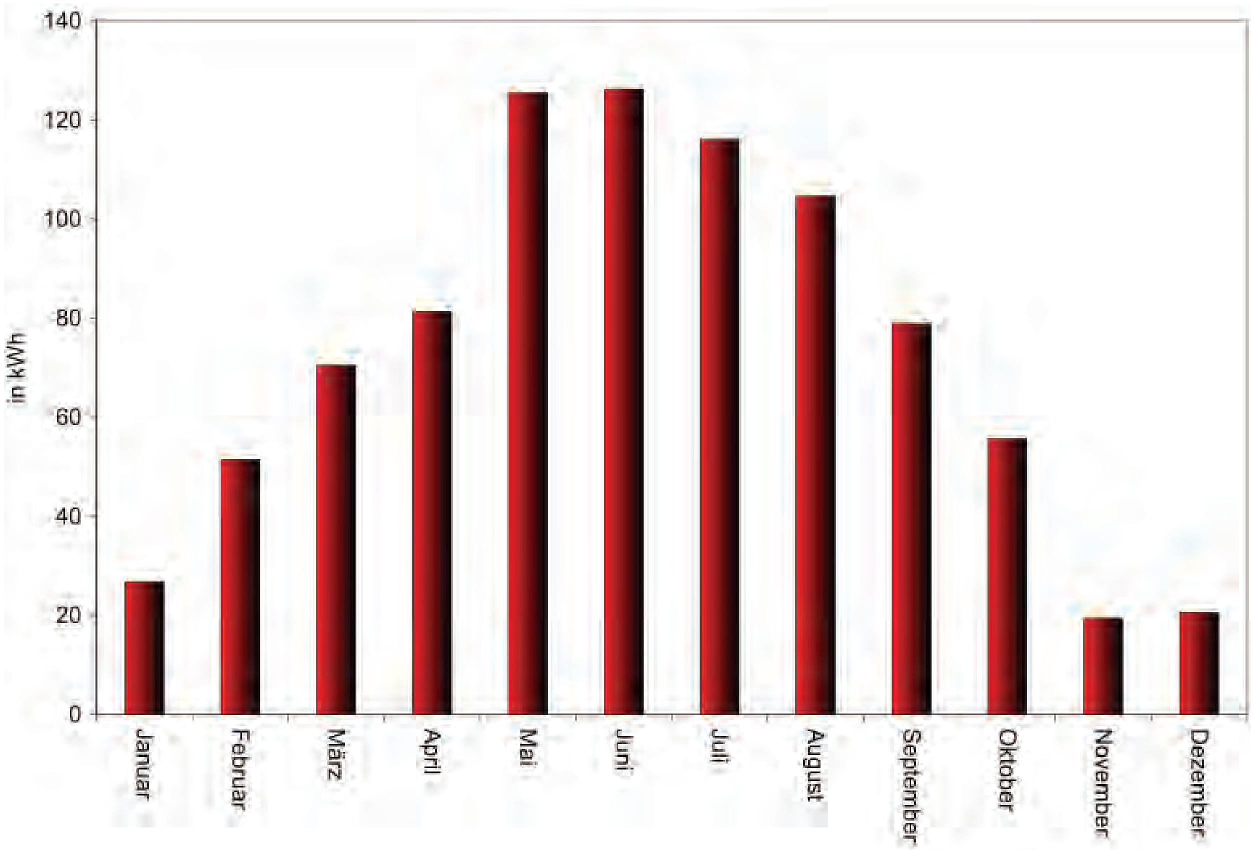


Figure 52: An example: The monthly energy production in northern Germany in 2008

The next figure shows the power-energy-diagram of a photovoltaic-system on an ideal, clear day with information concerning the solar radiation (global radiation).

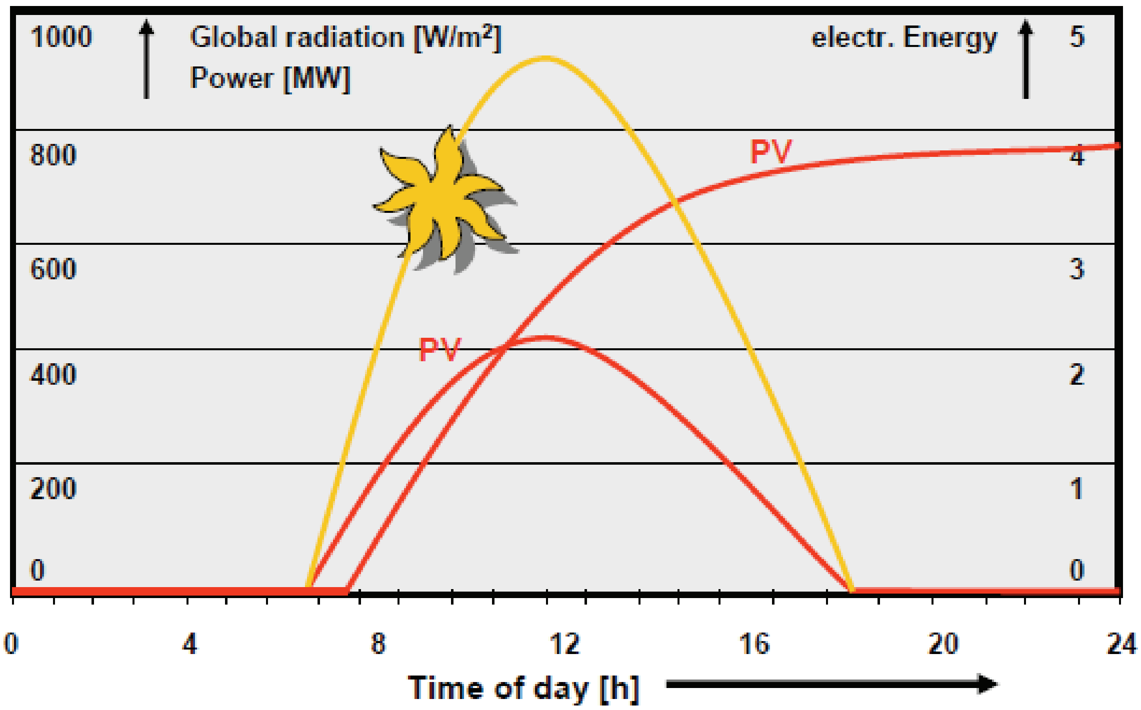


Figure 53: Solar energy-, power- and global radiation diagram on an ideal day

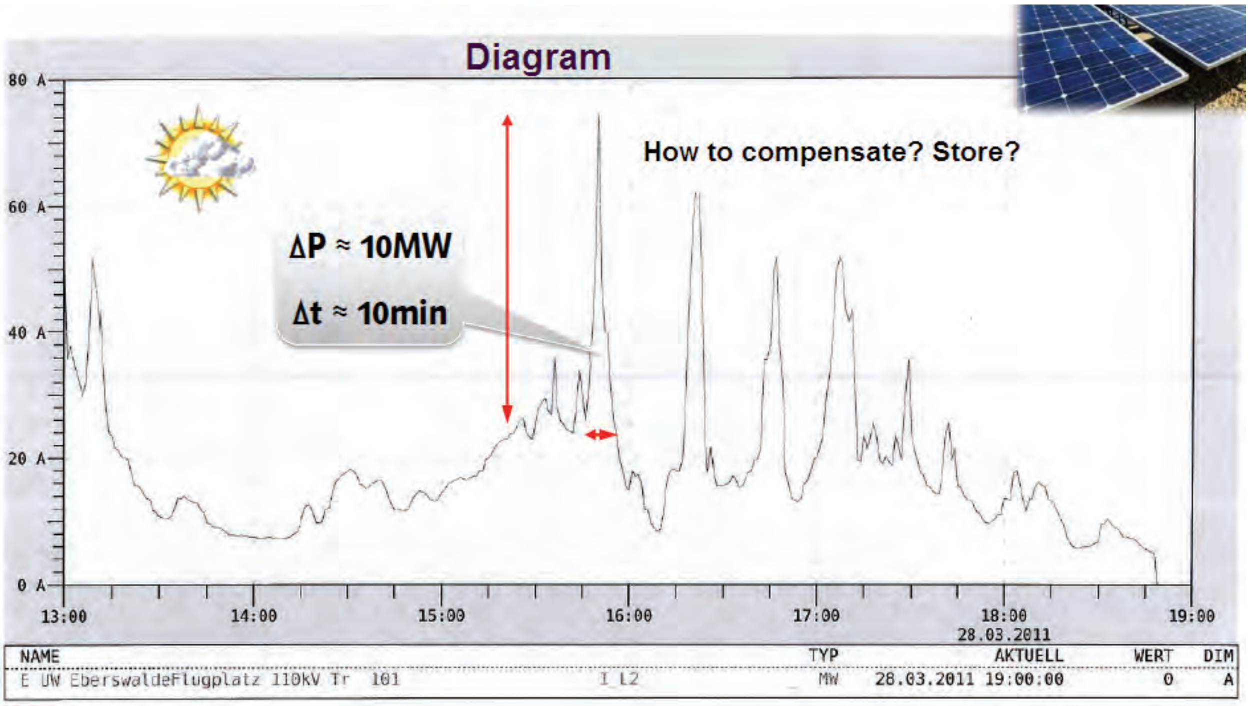


Figure 54: This is contrasted by a diurnal cycle of a photovoltaic area system with a power of 21 MV on a day with medium sky cover **Quelle: Behnke, E.ON edis AG**

One has to note the high, short production peaks. Within 10 minutes, the power fluctuation is 10 MW more and 12 MW less, respectively. To manage such production changes, a corresponding balancing energy that can be employed very quickly, is needed. Storage power stations are best suited for this. They can be activated and deactivated within minutes. Thermal power stations take much longer to reach the required power level. To shorten the startup-time, they can be used in idle state. This takes around a third of the primary energy (gas, oil, coal) required for nominal power – without producing electricity!

7.5.8 Impact of photovoltaic systems on the electricity network

The power grid is a very complex system with many variables. Since electrical energy cannot be stored in large quantities, it must be produced immediately when the current is drawn. If consumption and production are different, the line frequency is modified, which may lead to a failure of power supplies. The daily load curve for the example Germany (cf. Figure 55) is met by base load, intermediate load and peak load production.

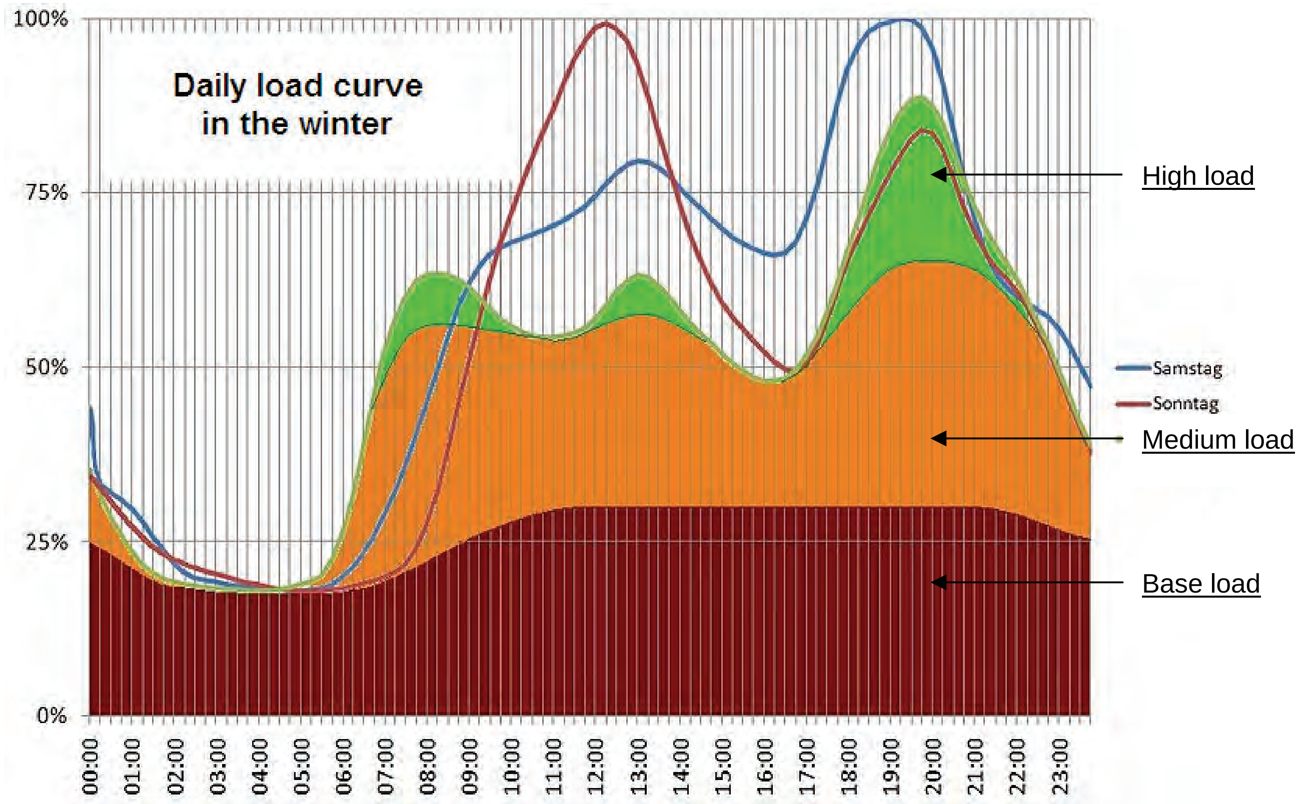


Figure 55: Electricity demand, VDEW daily load curve in the winter

The base load is the minimum electricity demand during a day. This demand is met today mainly by nuclear and coal power plants, and in the future perhaps by geothermal power plants that produce electricity around the clock. The medium load is covered by partially controllable power plants, mainly coal-fired power plants. For peak load coverage, gas and pumped-storage power plants are used. The management of the electricity grid can be planned with these conditions.

With the use of stochastic energy sources (solar and wind), the system is much more complex. To a certain degree, solar and wind energy can be planned with the help of meteorological forecasts. But deviations always have to be expected. To compensate for fluctuations, parallel power plants are necessary, but also to bridge the time, when for example there is no sun at night and on cloudy days. In order to control these fluctuations, new, highly efficient power control systems are needed in conjunction with smart grid systems so that not only wind but also solar systems can be activated and deactivated in the future.

In Germany, the installed capacity of photovoltaic systems is 25 GW. This corresponds to about one third of the power demand. Whether this installed power produces electricity depends only on the weather and time of day. It cannot be adjusted.

According to statistics, solar electricity is produced in Germany on average 870 hours per year. This is 22 TWh, or about 4% of the total consumption.

If the base-load power plants are replaced with photovoltaic systems, one has to install about 10 times the performance of the replaced plants (base load power plants produce about 8000 hours of electricity a year). Seasonal energy storage for 7100 hours when the sun does not shine, are not available.

Conclusion: Power generation from solar energy is especially suitable for the production of energy in peak load time. For a better control of the network, solar energy must not exceed a certain percentage of the share. In contrast to conventional power plants, PV systems do not have a rotating mass. These rotating masses contribute significantly to network stability.

Moreover, they are not a substitute for base load power plants because of the lack of suitable storage capacity in TWh.

7.5.9 Environmental impact

Basically, a photovoltaic system produces no CO2 during operation. For the production of photovoltaic modules with associated inverter, some energy is needed. Based on the European energy mix, this results in greenhouse gas emissions of 60 gCO2-eq/kWh.

The space requirements for photovoltaic systems cannot be neglected. With today's silicon modules, the installation of 1kW power requires about 6 to 8 m^2, with thin film cells approximately 15 m^2. The 24 GW installed capacity in Germany requires an area of 190 km^2. There are many roofs that are suitable for the installation of photovoltaic systems. But the question is whether homeowners or guardians of historical and esthetic aspects will give their assent to this.

7.5.10 Energy payback time (energetic amortization)

For systems with mono- or polycrystalline silicon cells, the payback time is around 1.7 years, for thin film cells 0.8 to 1.5 years.

7.6 Concentrated Solar Power

7.6.1 Introduction

In addition to the direct conversion of solar irradiation to electricity by means of photo-voltaic (PV) cells, an interesting indirect conversion technology, usually designated as “concentrated solar power” (CSP) is often advocated. In the CSP technology, solar irradiation is focused onto a focal point where it heats up a particular liquid substance with the eventual goal to drive a thermodynamic cycle to produce electric power. In contrast to PV, which is mostly utilized as a distributed, or decentralized, electricity-generation source, CSP is usually considered for large-scale applications.[6] CSP has the advantage over PV that it can incorporate large-scale (thermal) storage to deliver a “more constant” electrical output, if so desired. As a corollary, it is a generation technology that is dispatchable, clearly augmenting its value. A drawback for Europe is that the technology is only economically sensible in areas with ample direct solar radiation; southern Europe may be appropriate if the technology manages to become cheaper, otherwise northern Africa and the Middle East will have to be considered, which requires cautious reflections concerning security of supply when electric power is transmitted across the Mediterranean Sea.[7]

7.6.2 Direct Solar Irradiation - DNI

The amount of direct solar radiation is usually characterized though the concept DNI, being “Direct Normal Irradiance”. DNI is usually expressed as the amount of solar radiation impinging on a unit area (that is always kept) perpendicular to the solar rays coming in, on an annual basis. It is expressed in kWh/(m^2-a). For the hotspots in Northern Africa, the DNI can reach ~ 2500-3000 kWh/(m^2-a); whereas in Southern Europe, the numbers are of the order of ~ 1700-2000kWh/(m^2-a). Most middle European countries are situated in the window ~ 1000-1500 kWh/(m^2-a). (See figure 56.) Detailed maps showing the DNI of individual countries are available at the website of Solargis.[8] Other areas with very high DNI worldwide are e.g., the desert areas of Nevada-Arizona in the USA and a large part of Australia (IEA, 2010).

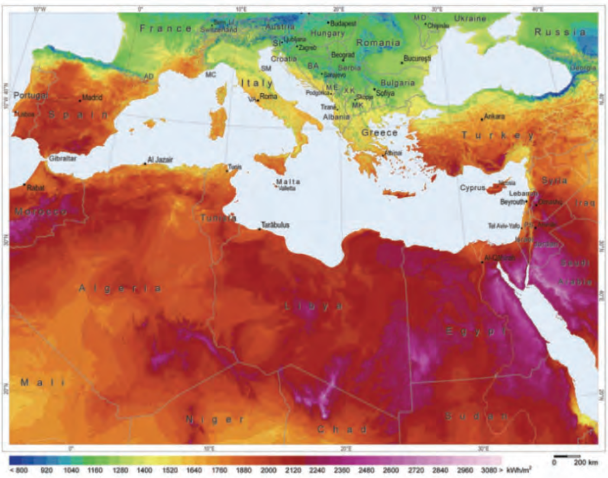


Figure 56: Direct Normal Irradiation (DNI) for the Mediterranean region. Ref: [EASAC, 2011] – in turn obtained from http://solargis.info

[6] Although it is certainly possible to consider large-scale PV installations and local decentralized CSP-facilities.
[7] Security of Supply is always a crucial issue when electric power is relied upon from an “external partner” because of the instantaneous character of electric power. Other energy carriers have the advantage of being able to rely on buffer capacities.
[8] http://solargis.info/doc/71

7.6.3 CSP Solar Receiver Technologies

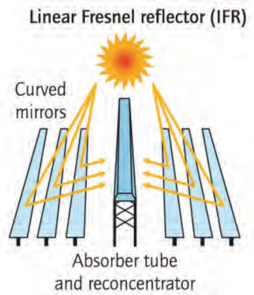
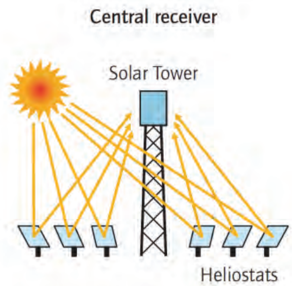
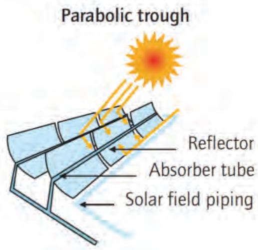
Following the document of the CSP Roadmap outlined in [IEA, 2010], four categories of CSP technologies can be distinguished. As indicated in Figure 57, one differentiates between fixed and mobile receivers, and linear and point focus types.

Focus type / Receiver type	Line focus Collectors track the sun along a single axis and focus irradiance on a linear receiver. This makes tracking the sun simpler.	Point focus Collectors track the sun along two axes and focus irradiance at a single point receiver. This allows for higher temperatures.
Fixed Fixed receivers are stationary devices that remain independent of the plant's focusing device. This eases the transport of collected heat to the power block.	**Linear Fresnel Reflectors**	**Towers (CRS)**
Mobile Mobile receivers move together with the focusing device. In both line focus and point focus designs, mobile receivers collect more energy.	**Parabolic Troughs**	**Parabolic Dishes**

Figure 57: CSP technology families. Ref: [IEA, 2010]

Table 2 continues with the same outline as Figure 57 (i.e., same columns and rows), clarifying the types with an illustrative picture. As can be seen, the following broad categories exist: Linear Fresnel Reflector (LFR); a Central Receiver or Solar Tower, a Parabolic Trough, and a Parabolic Dish.

Table 2: CSP technology families. [EASAC 2011 & IEA, 2010]

Receiver Type \ Focus Type	Line Focus	Point Focus
Fixed		
Mobile		

7.6.4 CSP Conversion Technologies

Figure 58 shows the basic principle of the conversion process of "solar heat" towards electric power. The thermal cycle is usually a Steam Rankine cycle, or, for the parabolic dishes, it is a Stirling engine.[9]

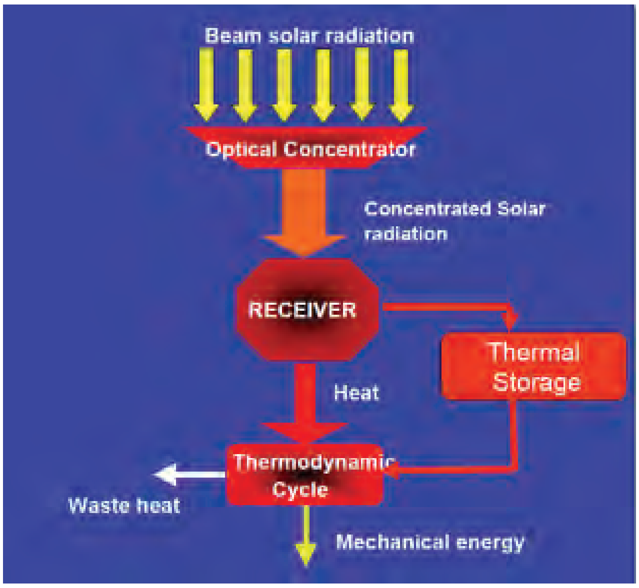


Figure 58: Principle of conversion technology from solar heat to electricity. Ref. [A. Lopez, CIEMAT, 2008]

For simplicity, and by way of example, the following focusses on the conversion process of large scale plants. For a more complete discussion, the reader is advised to consult the literature provided in the bibliography.

7.6.4.1 Steam Cycle with Storage

The most basic concept consist of a setup whereby the heated fluid in the receiver transfers its thermal energy to the secondary side of a heat exchanger (usually water), and convert it to steam which in turn is led through a steam turbine. To avoid discontinuous operation and to allow load following and/or dispatching, it is convenient to foresee a storage option. Usually, a molten salt, stored in two tanks is utilized towards that goal (although other possibilities exist – see [EASAC, 2011]). Figure 59 shows the basic set up.

[9] A Stirling engine is a "classical" thermodynamic engine with a theoretical efficiency equal to the Carnot efficiency. In contrast to Otto and Diesel engines, which are internal combustion engines, a Stirling is an external "heating" engine. In addition, the work ratio (being the work out over the work put in to make the engine operate) of a Stirling is much higher than for a Carnot cycle. As a matter of fact, the work ratio of a Stirling is numerically equal to the Carnot efficiency. Because of practical reasons (having to do with, a.o., sealing and leakage), the practical usage of Stirlings has historically been lagging behind other engine types.

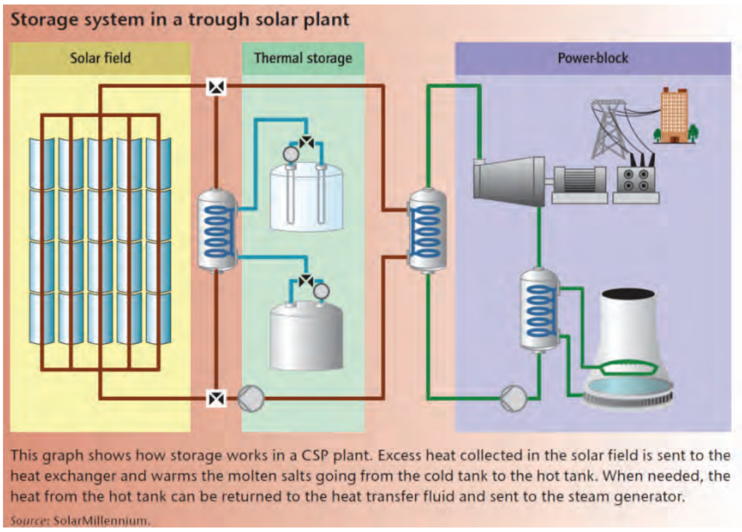


Figure 59: Basic set up of power plant with molten salt storage. Ref. [IEA, 2010]

Figure 60 shows two typical reasons for the thermal storage. In the left-hand side panel a load-following profile is aimed at ([EASAC, 2011]) whereas the right-hand side panel strives for a flat output, thereby also relying on additional combustion by fossil means ([IEA, 2010]).

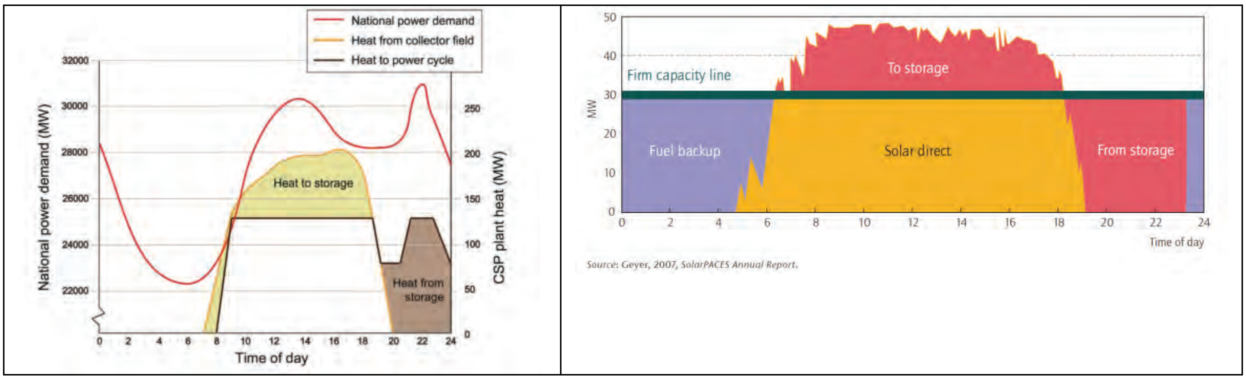


Figure 60: Illustration of increased value of CSP plants with storage. LHS Ref [EASAC, 2011] and RHS Ref. [IEA, 2010]

7.6.4.2 Integrated Solar Combined Cycle (ISCC)

To help launch a technology such as CSP, it is useful to consider “hybrid” solutions, whereby a new technology can develop in the mainstream or “wake” of another, more mature technology. A typical example is the so-called Integrated Solar Combined Cycle, whereby the solar heat of the receiver is utilized to heat the feedwater for the Rankine cycle of a natural gas-fired combined cycle (with gas turbine). It thus concerns a solar-assisted CCGT. A typical example is shown in figure 61. The concept is explained in e.g., [Kelly et al., 2001] and in [Hosseini et al., 2005].

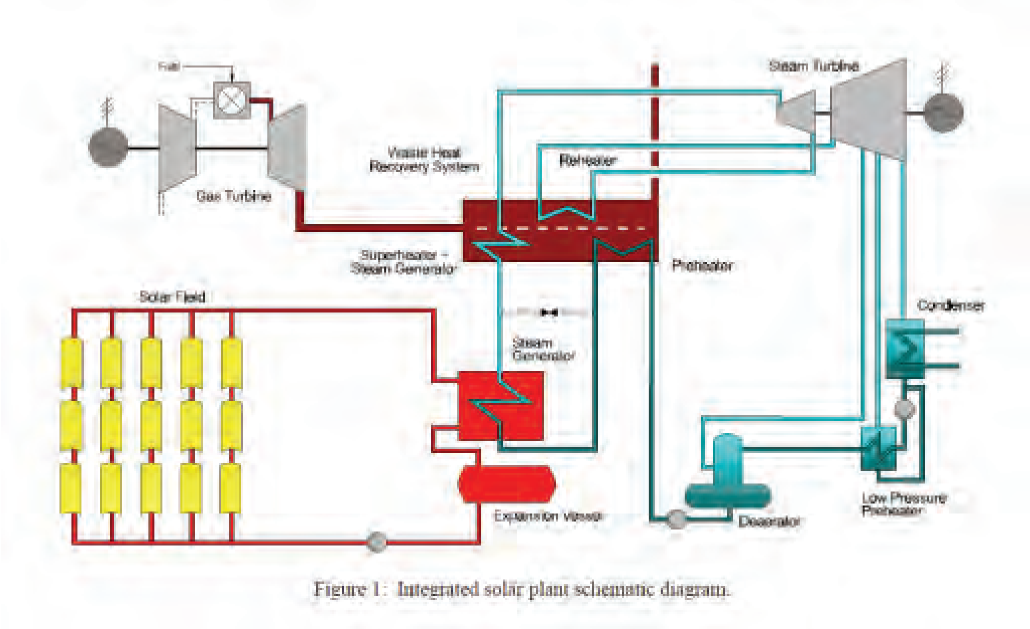


Figure 61: Example of a hybrid concept, the combination of solar heat to heat up feedwater in a CCGT. This concept is referred to as Integrated Solar Combined Cycle (ISCC). [Kelly et al., 2001]

7.6.4.3 Solar-Driven Gas Turbine Combined Cycle (SD-GTCC)

Going one step further than a solar 'assisted' combined cycle, [DLR, 2009] and [Heide et al., 2009] present a gas turbine whereby the thermodynamic fluid (i.e., the gas) is heated by the solar tower, rather than in a combustion chamber. It is fair to speak about at solar-'driven' gas turbine (with a following steam cycle). An example of the setup is shown in figure 62.

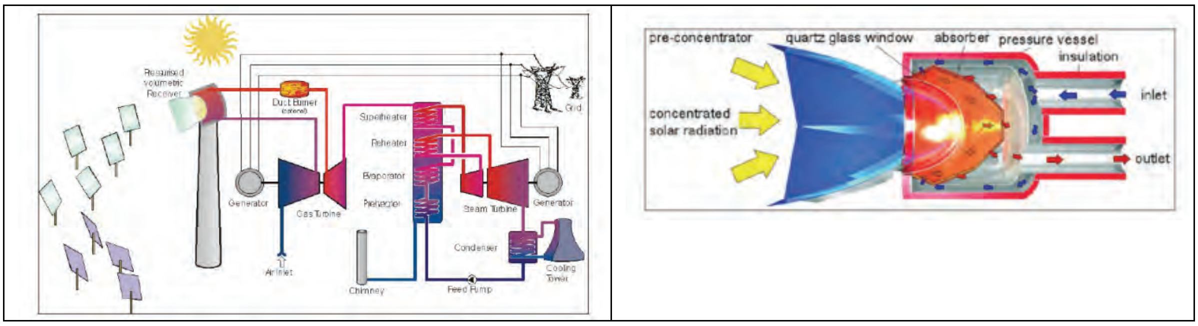


Figure 62: Set up of a solar-driven gas turbine complemented with a steam cycle. CCGT. The RHS of the figure shows the "replacement" of the combustion chamber. [DLR, 2009].

7.6.4.4 Cost Aspects of CSP

To have an understanding of the current and future cost aspects of CSP, it is important to put them into perspective with repect to other technologies. [IEA, 2012] privides an updated comparison; it is repeated below in Figure 63. As is clear from the figure, CSP plants are still too expensive compared to classical thermodynamic plants, and to other renewable technologies. Expectations are moderately positive. Because of the expected large capacity factor of CSP with storage, the Levelized

Cost of Electricity (LCOE; in € /kWh) may be of the same order of magnitude as future PV, or even cheaper.

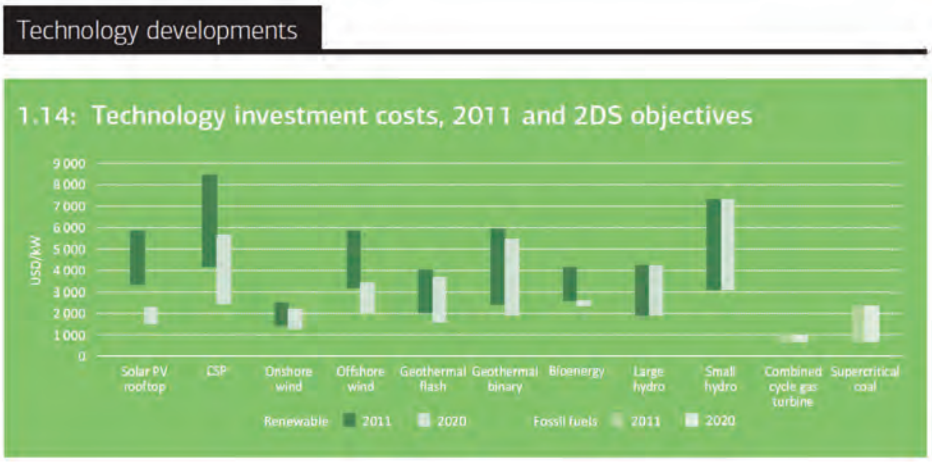


Figure 63: Specific-cost comparison of different technologies. The dark green bars are the current estimates (2011) with a range of lower and upper bounds. The white/gray bars are the desired cost ranges to be reached by 2020 to play a role in the 2°C temperature-increase scenario (450 ppm GHG; called the 2DS scenario). [IEA, 2012].

7.6.4.5 Current Situation and Outlook of CSP

Expectations were high on development of CSP, but they have not materialized. According to the IEA 2012 report “Tracking Clean Energy Progress” [IEA, 2012], «The first commercial plants, built in the 1980s in the United States, are still in operation, but further project development lagged in the 1980s and 1990s. Today, the industry has hundreds of MW under construction and thousands under development worldwide. Spain has taken over as the world leader in CSP and, together with the United States, accounted for 90% of the market in 2011. Algeria, Morocco and Italy also have operational plants, while Australia, China, Egypt, India, Iran, Israel, Jordan, Mexico, South Africa and the United Arab Emirates are finalizing or considering projects. While the project pipeline is impressive, the economic recession and lower PV costs show evidence of diverting and slowing CSP projects (e.g. the United States converted a number of planned CSP projects to PV).

As has been observed by the European Commission’s Advisory Group on Energy [AGE, 2012], several CSP demonstration projects have been initiated over the last 5 years or so thanks to substantial feed-in tariffs in Spain and loan guarantees in the US. Further deployment in the near future is questionable, since those support mechanisms are both now suspended and CSP is not yet commercially viable without subsidies. Because of its interesting characteristics, notably its dispatchability, further R&D efforts are, however, justified, especially to make the “mirrors” & receivers cheaper, to optimize the thermodynamic cycle and the thermal storage, and to investigate opportunities with hybrid concepts.

7.7 Biomass technologies for power plants

7.7.1 Introduction

Current energy supplies in the world are dominated by fossil fuels. Nevertheless, about 10–15% of the demand is covered by biomass resources, making biomass by far the most important renewable energy source used to date. On average, in the industrialized countries biomass contributes some 9–13% to the total energy supplies, but in developing countries the proportion is as high as a fifth to one third. In quite a number of countries biomass covers even over 50–90% of the total energy demand. A large part of this biomass use is however non-commercial and used for cooking and space heating, generally by the poorer part of the population.

The major applications of biomass fuels for electricity generation are:

1. Co-firing of biomass with coal in power plants and coal-fired district heating plants
2. Biomass-fuelled district heating combined with small-scale electricity production (CHP)
3. Gasification in a combined cycle for electricity production
4. Electricity production from waste biomass (waste incineration, landfill gas recovery, anaerobic digestion.

One of the fastest and easiest ways to increase the share of renewables is by replacing fossil fuels with biomass, and the co-firing of biomass fuels in mainly large coal-fired units, and thereby replacing part of the coal, has been adopted all over the world over the past few years. This is a relatively quick method to exchange traditional fossil fuels such as coal and fuel oil, with a sustainable large scale of solid and liquid biomass types, like wood pellets or palm oil, in order to reach environmental incentives.

Co-firing percentages in conventional pulverized coal fired power plants have increased from roughly 1-10% of energy input, to well over 20% over the past decade. In some specific pulverized coal fired installations, 100% conversion from coal to biomass has been demonstrated.

7.7.2 Co-firing concepts

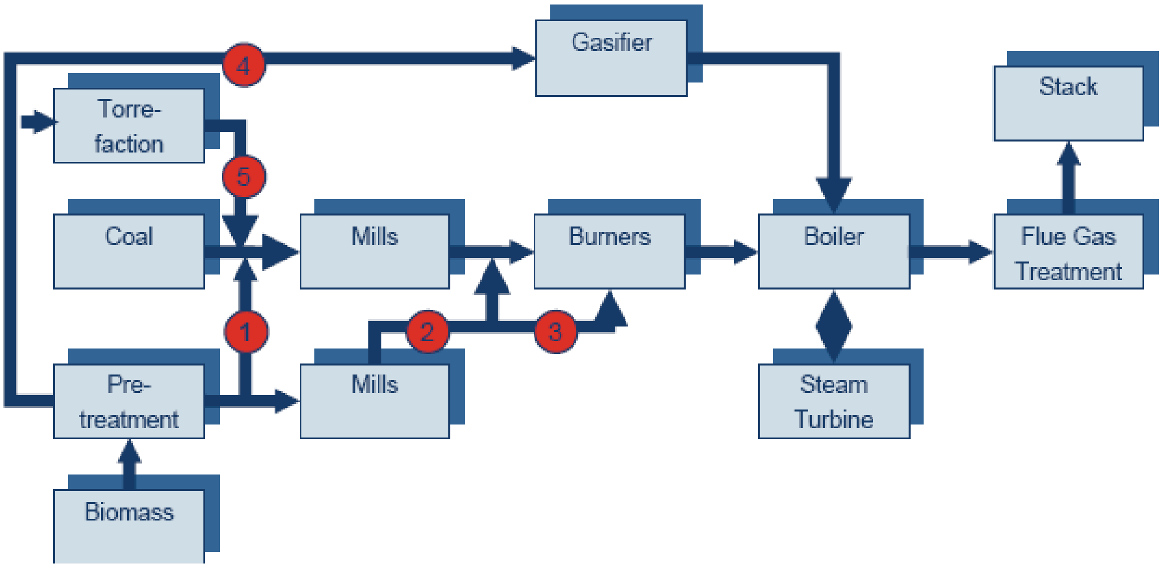


Figure 64: The principal direct and indirect co-firing routes [Kema Consulting, 2007]

Most of biomass co-firing projects worldwide have involved the utilization of solid biomass materials and have been implemented as retrofits to existing pulverized coal-fired power stations. The options for co-firing in this type of plant can be categorized as follows, and as illustrated in the figure:

- Direct co-firing: co-firing by pre-mixing the biomass with the coal and co-milling, i.e. route 1 and 5
- Direct co-firing: co-firing of pre-milled biomass to the coal firing system or furnace, route 2 and 3
- Indirect co-firing: involves the gasification of the biomass and the combustion of the product fuel gas in the furnace, as indicated by route 4
- Parallel co-firing: involves the combustion of the biomass in a separate combustor and boiler and the utilization of the steam produced within the coal-fired steam and power generation systems.

All of the key co-firing options in figure 64 have been successfully applied at least at demonstration scale, apart from route 5 which involves the utilization of torrefied biomass materials. These are not yet available in industrial quantities.

7.7.3 CHP concepts

As decentralized CHP applications based on biomass combustion are seen plants with nominal capacities below about 20 MW_e. According to the state-of-the-art the following technologies based on biomass combustion are well suited for decentralized biomass CHP plants:

- Stirling engines up to an electric capacity of about 100 kW_e
- Organic Rankine Cycle (ORC) processes in a capacity range between 400 and 1500 kW_e
- Steam turbine processes for capacities of more than 2000 kW_e

Both ORC processes and steam turbine processes have already reached market introduction. Stirling engines are in operation as pilot plants; their market introduction is expected in the near future.

Besides biomass combustion, also biomass gasification can in principle be applied in the field addressed. The relevant technologies are:

- Fixed bed gasification and gas engine
- Fluidized bed gasification and gas engine
- Fluidized bed gasification and gas turbine.

Biomass CHP systems based on gasification technologies have, however, not achieved market introduction yet (no mature technology).

7.7.4 Integrated gasification combined cycle

An integrated gasification combined cycle (IGCC) is a technology that turns biomass into gas-synthesis gas (syngas). It then removes impurities from the gas before it is combusted and attempts to turn any pollutants into re-usable byproducts. This results in lower emissions of sulfur dioxide, particulates, and mercury. Excess heat from the primary combustion and generation is then passed to a steam cycle, similarly to a combined cycle gas turbine. This then also results in improved efficiency compared to conventional pulverized coal.

There are several refinery-based IGCC pilot plants in Europe that have demonstrated good availability (90-95%) after initial difficult periods.

An IGCC success story has been the 250 MW Buggenum plant in The Netherlands. This coal-based IGCC plant currently uses about 30% biomass as a supplemental feedstock. The owner, NUON (now Vattenfall), is paid an incentive fee by the government to use the biomass. NUON is constructing a 1,300 MW IGCC plant in the Netherlands. The Nuon Magnum IGCC power plant will be commissioned in the next years.

7.7.5 Waste installation

At present, most biomass power plants burn household, industrial, lumber, and agricultural or construction/demolition wood wastes. Direct combustion power plants burn the biomass fuel directly in boilers that supply steam for the same kind of steam-electric generators used to burn fossil fuels. With biomass gasification, biomass is converted into a gas - methane - that can then fuel steam generators, combustion turbines, combined cycle technologies or fuel cells. The primary benefit of biomass gasification, compared to direct combustion, is that extracted gasses can be used in a variety of power plant configurations.

7.8 Hydro power

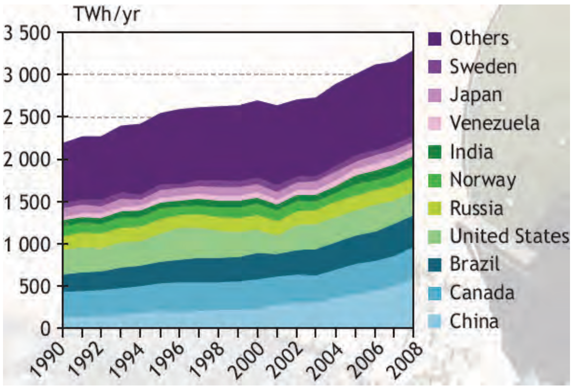
7.8.1 Introduction

Water powered scoop wheels for irrigation purposes had already been known in Mesopotamia in the 5th Century BC. They are probably the oldest machines used by humankind. The first documented water powered grinding mills were used in Asia in the 3rd Century BC.

At the beginning of industrialization, water power was used to drive the newly developped machines such as lathes, drilling machines, etc.. By means of water powered transmission shafts that ran through entire factory halls, individual machines could be powered with transmission belts coupled to the shaft. With the development of electric generators, the employment of purely mechanical energy disappeared.

7.8.2 Hydroelectric power production

Hydroelectric power plants currently produce approx. 3400 TWh electric energy worldwide. This corresponds to around 16.5 % of global electricity production. Around 1400 TWh are generated in OECD countries, i.e. 13 % of the total production, outside of the OECD countries it is 1900 TWh (20 % of the total production).



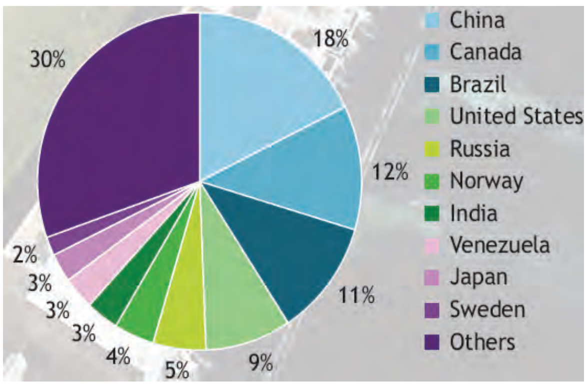


Figure 65: Hydropower, IEA

It is currently estimated that the potential for a technical use of hydropower amounts to approx. 16 000 TWh per year worldwide.

7.8.3 Function of hydroelectric power plants

The power of flowing water can be used by different types of hydroelectric power plants. The amount of energy produced either depends on the available flow rate or on the drop height, or both.

- \- Hydroelectric power plants situated in rivers are called Run-of-the-river power plants. They use a large flow rate with a low gradient and are also called low-pressure power plants, with a drop height of up to 15 meters. Hydroelectric power plants are often not only used to generate electricity but also to protect against flooding or to mitigate bank and bed erosion.
- \- Storage power plants use the water accumulated by a dam. Generally, the water falls from a great height onto the turbine and produces large quantities of energy with smaller amounts of water.

Medium pressure power plants have a head of 25-400 meters, high pressure power plants of over 400 meters. High-pressure power plants can only be realized in mountain regions and are primarily used to cover peak loads.

- \- Pumped storage power plants feature a lower elevation reservoir where water can be stored. This water is mainly pumped up to the higher reservoir with excess energy (e.g. wind energy). When pumping, around 20% more energy is needed than is gained from production.

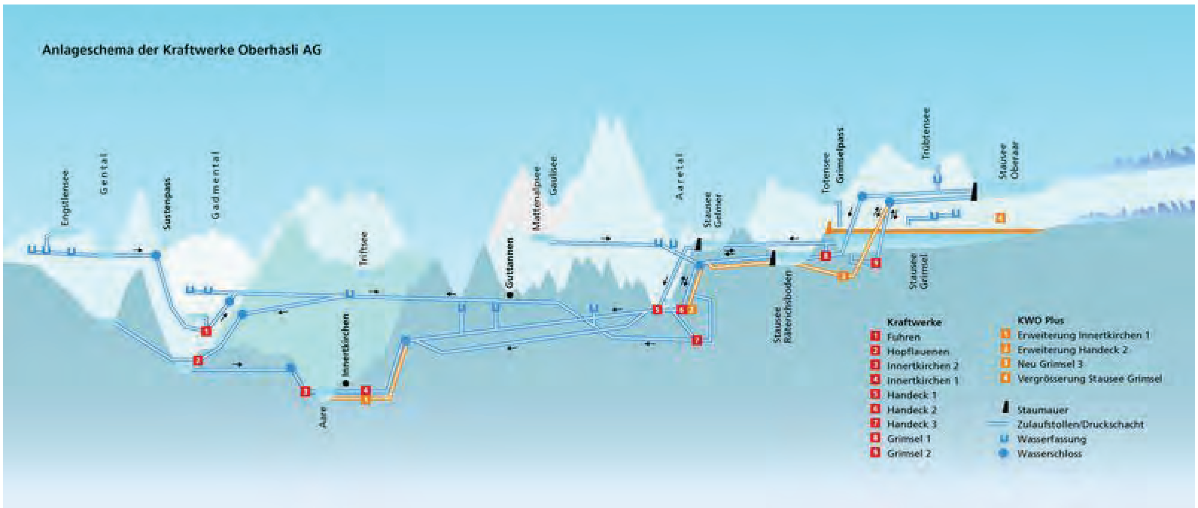


Figure 66: Hydraulic system, Kraftwerke Oberhasli

7.8.4 Turbines of hydroelectric power plants

Today, the most common turbines used in hydroelectric power plants are

- Kaplan turbine

- Francis turbine
- Pelton turbine

The Kaplan turbine is mainly used at low heads and large amounts of water, i.e. in run-of-the-river power plants. It employs both the kinetic and the potential energy of the flowing water. Thus it reaches maximum efficiency already at 40% of its nominal power. A special form of the Kaplan turbine is the bulb turbine, where the generator and the turbine are mounted in a housing in the water-carrying pipe. Bulb turbines are primarily used in smaller rivers.

A further development of the Kaplan bulb turbine is the Straflo turbine. Turbine and generator form a unit in one plane, i.e. the Straflo turbine has no shaft.

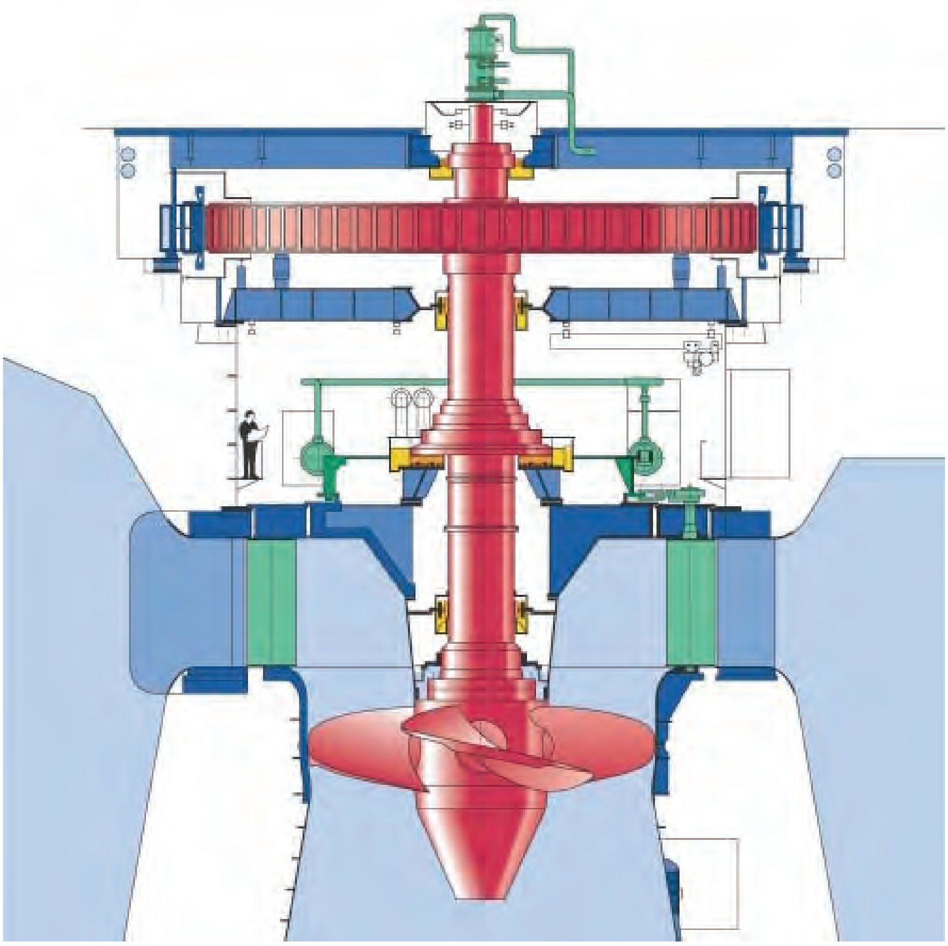


Figure 67: Kaplan turbine, Wikipedia

The Francis turbine is used mostly in case of heights between 50 and 400 meters. The part-load performance is worse than that of other turbines. The maximum efficiency is reached at 70 - 90% of the rated power. The efficiency decreases quite quickly with decreasing rated power.

One of the world's largest Francis turbines is used in the Itaipu hydroelectric power plant. The performance of each of the 20 turbines is 715 MW.

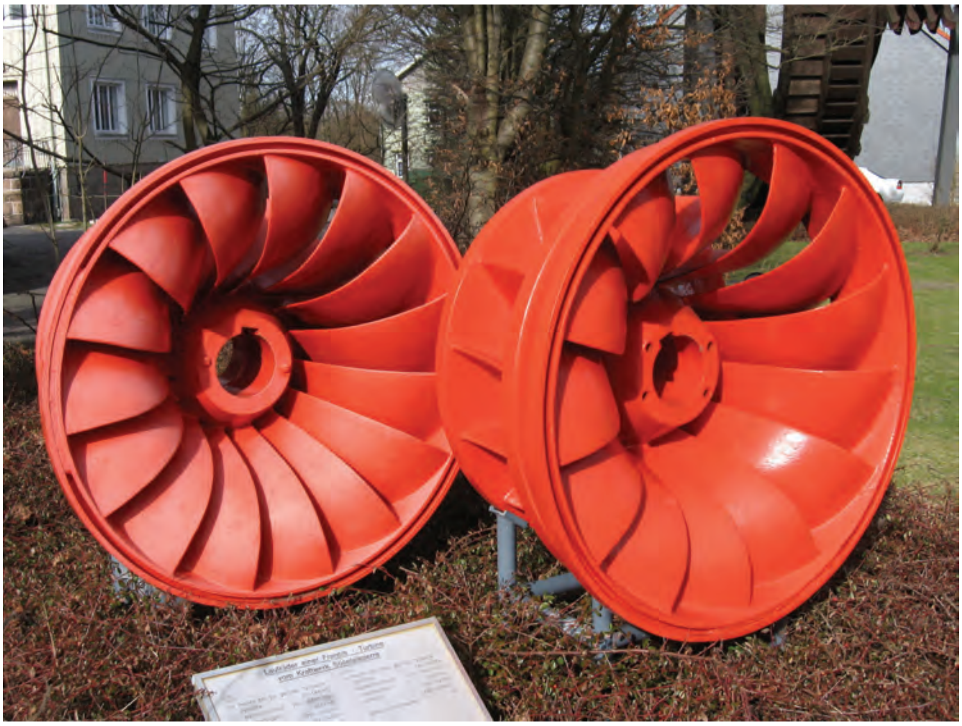


Figure 68: Francis turbine (Wikipedia)

The Pelton turbine is mainly used at large heights (200 to over 1000 meters). The turbine power can be controlled via nozzles. They convert the potential energy of the flowing water into kinetic energy. The part-load behaviour is very interesting. The maximum efficiency is already achieved at about 30% of the rated power.

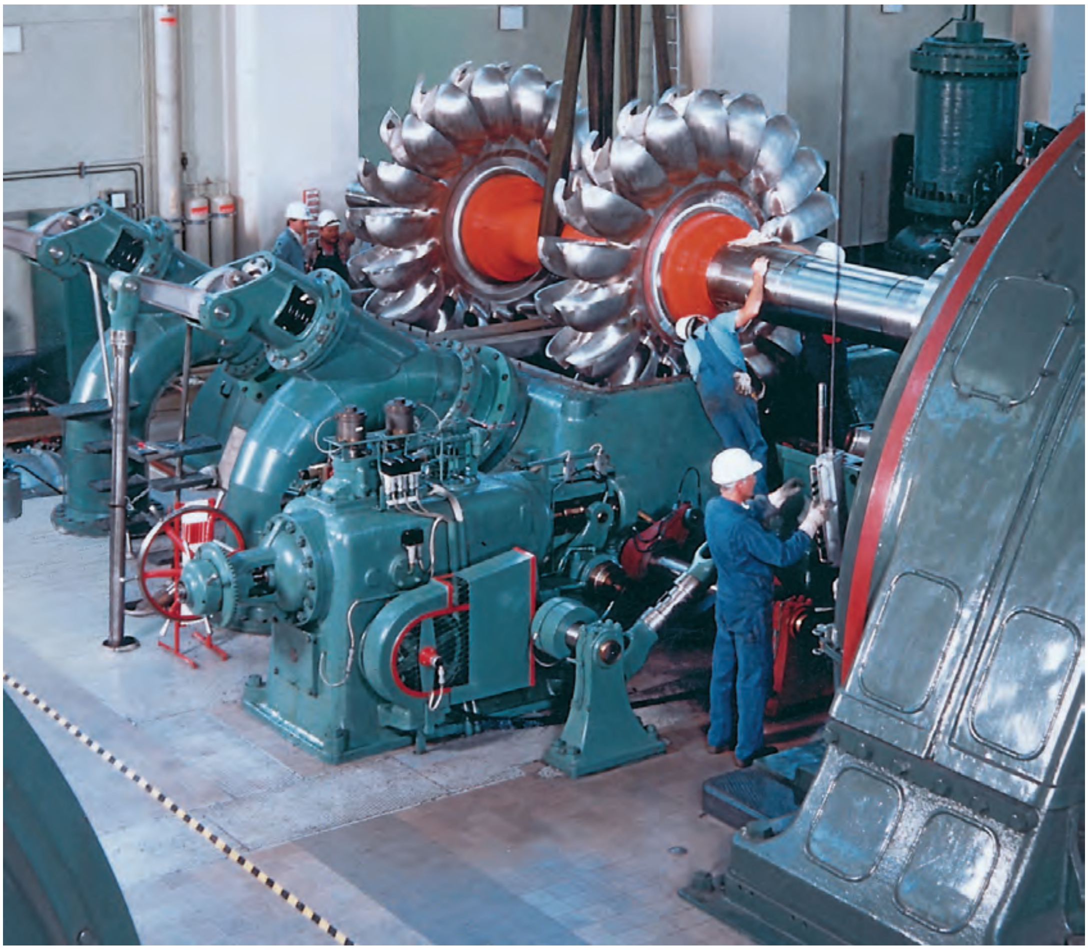


Figure 69: Pelton turbine (Wikipedia)

7.8.5 Availability of hydropower

Except for the tidal and ocean current power plants, the amount of water available for power production depends on the season and meteorology.

The river flows in our latitudes reach their lowest level during winter months. However, when the snow melts or during heavy rains, our rivers can have over 3 times as much water as in the winter. In other latitudes, the water quantity depends on the rainy season or monsoon. Climate change could have an impact on the rain quantities and on the periods of rain. With the rise of the snow line, the natural storage in the form of snow disappears partially. And if the glaciers continue to melt, the quantity of the water provided by the glaciers will be reduced continuously.

Conclusion: Long-term forecasts concerning the availability of water for hydropower production are difficult.

7.8.6 Environmental impact

Worldwide, around 85% of renewable electric energy is produced by hydropower, i.e. around 20% of the total electricity production. This energy is CO2-free and almost always available. The production rate depends on the weather, seasonal and climatic influences. Reservoirs can be used for flood protection.

The construction of hydroelectric plants always has an impact on the landscape, the extent of which depends on the chosen technology. If a reservoir is used, large areas or whole valleys are usually flooded. For river power plants, parts of the watercourse is turned into reservoirs. Caught water is led in pipes to the power plant. The residual amount of water (handled differently depending on the country, sometimes not required) change the landscape and the microclimate along streams and rivers.

7.8.7 Investment costs

The investment costs of hydropower plants are relatively high. However, as power plants are designed for a long life (over 80 years for fixed structures), and only a moderate water tax might have to be paid for the primary energy “water”, the costs of energy production are low compared to that of other renewable energies. Future environmental impact assessments with appropriate project adjustments and higher residual amounts of water could change production costs. On the other hand, the phasing out of nuclear energy could lead to a more lenient assessment of impacts on ecology and landscape.

7.8.8 Electricity production costs

The production costs are mainly influenced by the investment costs, the depreciation of the investment, operating costs and a possible water rate. Power plants built in the 1960ies have production costs in the range of 4 to 10 Euro cents. Newer power plants, especially in the mountains, have a cost range from 15 - 20 € cents.

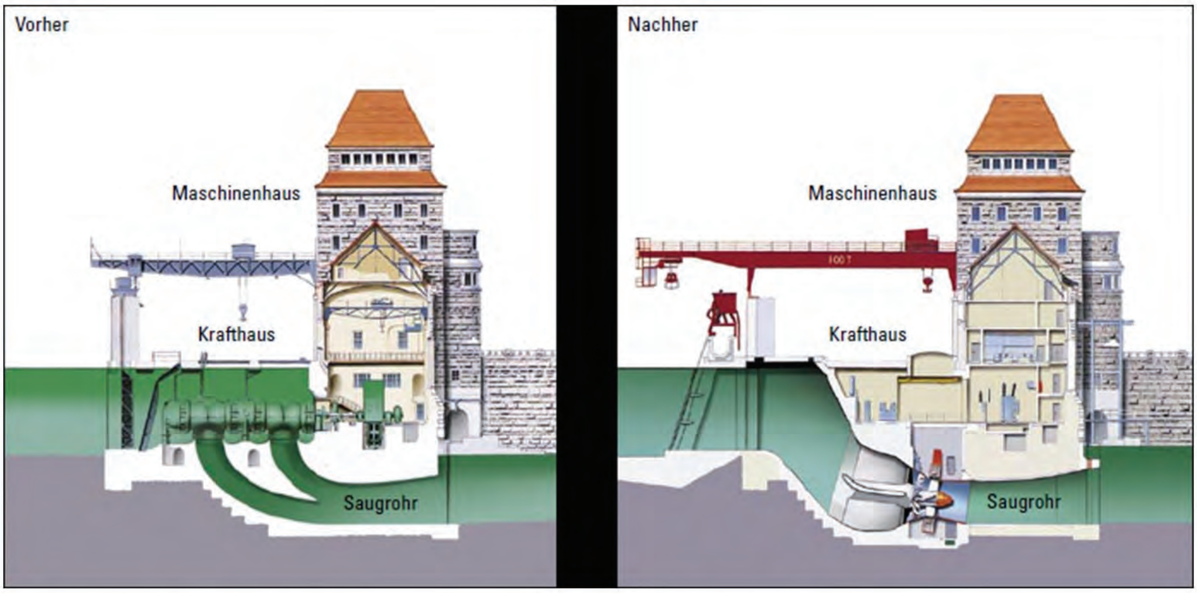
7.8.9 Expansion potential of hydropower

Especially in South America and Asia, there is still a great potential of unused hydropower. The main problem is the distance between the hydropower potentials and the consumers.

In Central Europe, hydropower is developed quite strongly. In Switzerland, approximately 95% of the waters are used. With the promotion of renewable energies, the construction of small power plants has become attractive.There is, however, an increasing opposition in the general public to a complete use of all remaining waters, and particularly to building activities in areas of unspoiled nature. A potential lies in the renewal of existing power plants by increasing system efficiency or change of use potential.

7.8.10 New technologies

Currently, there are no groundbreaking innovations. The Straflo turbine has not had a significant breakthrough – it still remains a niche product.



With Francis Turbine until 1981 since 1993 with Straflo Turbine

Figure 70: Hydropower plant Laufenburg, Switzerland

For smallest power plants, there are attempts on the basis of water vortex power plants. The focus lies on a further development and improvement of conventional technology with Kaplan, Francis and Pelton turbines.

8. Storage technology options

8.1 Introduction

In the past, energy storage has not been an important issue as all the fossil fuels could very easily be stored, e.g. in tanks, caverns or piles. Today's storage systems, mainly pumped hydro power plants, have been used in order to optimise the operation of the thermal power plants. However, most renewable energy sources (RES) have no inherent storage capabilities and thus the power generation directly follows the actual conditions (wind speed, solar radiation intensity, water flow of rivers). These conditions vary randomly in time and space: they depend on seasonal, meteorological or other conditions and are not controllable. Forecast is possible to some extend but even high prediction errors cannot be excluded. Recent studies indicate that with a further deployment of RES, its grid integration is likely to become an issue due to shortages of balancing capacities and bottlenecks at different grid levels. Existing conventional thermal generation plants offer only a limited potential of short term balancing power but also their total capacity will continuously decline in the coming decades. A lack of power from renewables can be compensated in principal by providing sufficient conventional generation capacity, whereas we will also need to cope with situations with excess power from renewables. Especially with highly increasing penetration rates (e.g. Germany expects 80 % of renewables by 2050), we will see more and more periods where the power production from renewables will be higher than the local demand. Balancing between regions or demand-side management will be the first choice in order to cope with such situations. If these possibilities are exhausted, only storage systems may help to avoid the rejection of the valuable energy from renewables - at least to some extent. Of course a total storage, e.g. high power peaks with short duration, will not be possible for economic reasons.

8.2 Need for storage systems and requirements

Additional energy storage capacity will be needed for balancing fluctuations at different time-scales for which adequate control schemes apply. Random imbalances between generation and load may be positive or negative. Immediate and short term balancing is the task of the **primary control**. The prescriptions specified in the grid code for providing primary control are very tough, asking for full power within 30 seconds. Today primary control power is provided to a high amount from a large number of thermal power stations, spread over the whole grid. When increasing the amount of renewables, the associated decreasing number of thermal power plants will become a challenge. Pumped hydro power stations - if not already running - are not able to correspond to this prescription whereas flywheel systems or battery energy storage systems could provide full power immediately. The power needs to be delivered only for a relatively short duration (up to 15 minutes). This would be the optimal time scale for flywheels whereas most battery systems are best suited for discharge times in the range of a few hours. Today, the maximum total power for primary control in the UCTE-Grid is 3000 MW, based on the simultaneous outage of two units of a large power plant. In the future, a more frequent need and higher power values are to be expected due to high unpredictable fluctuations of renewables (imbalance between forecast and real generation). Also the outage of a high power interconnector could become an issue in the future, especially when there will be a need for a high power overlay-grid.

Secondary control power is intended to back-up the primary control in order to re-establish the power balance inside the control zone where the imbalance occurred. The activation of the secondary control power should start together with the primary control and needs to be fully activated after 15 minutes latest. The power should be deliverable for at least 1 hour. Today this has become the daily job for pumped hydro power stations – meaning more frequent operation - although they have not been designed for (typically designed for load levelling between day and night). Up to now, the typical secondary control reserve power for each control zone was in the range up to 3000 MW, depending on the existing generation system. As secondary control is linked to the primary control, a corresponding increase of control power needs to be considered in the future.

If there is a longer lasting need for control power within a dedicated control zone, the secondary control needs to be superseded by the **tertiary control**, sometimes also called “**minute reserve**”. Primary and secondary control are activated automatically, whereas the power needed for tertiary control is activated on demand by the system operator, e.g. via phone call to a power station. Generation units which might be called for delivering tertiary control power should be able to ramp up or down within 15 minutes. Up to now tertiary control power has been provided by thermal power stations in order to replace the high-price power from storage plants by cheaper units. In the future the situation will be different, depending on the available generation system. As there will be also a need for long-term storage systems with a high energy capacity in order to bridge several days or even weeks (s. below), such plants will be probably called for tertiary control and a clear discrimination between the terms may become difficult.

In an unbundled system, the provision of control power (all stages) has been appointed to the grid operator, whereas the provision of scheduled power – following also the forecasted weather conditions - lies in the responsibility of the energy providing companies. When the day-ahead forecast indicates a lack of power from renewables, the energy provider has to call for corresponding **reserve power**. Such predictable unavailability can be short term, e.g. intra-day or day/night for PV, but can last also for several days or weeks, e.g. stable weather conditions in Central Europe are the cause for long-lasting periods with almost no wind over a wide area. Furthermore the availability of wind and solar energy can highly vary from one year to the other. Especially in future power systems with high penetration of renewables this has to be taken into account and corresponding reserve capacities have to be provided. Storage systems able to cope with such situations would need huge storage capacities, e.g. for Germany up to some tens of TWh could be necessary.

The handling of predictable excess power is still not solved. Up to now this situation occurs only locally and the export to neighbouring regions is mostly possible. In the future this excess power will be used for charging the large storage systems.

Beside the provision of control or reserve power, the bridging of **bottlenecks** in the grid is discussed to be another application for storage systems. But up to now the installation of additional transmission capacity is by far less expensive compared to a storage system.

8.3 Characterization of storage systems

Energy storage systems can be characterized by a set of parameters. For the selection of a suitable energy storage system it is necessary to know as exactly as possible the characteristics of typical duty cycles, their frequency and the required response time to full power. In this context also the load following capability and the power-flow reversal (e.g. change from charging to discharging) may become important for certain applications. These data define the energy throughput and the number of cycles per time unit. The efficiency of storage systems can be described by their cycle losses and stand-by losses (including power conversion system and auxiliaries). For many storage technologies the efficiency depends also on the duty cycle, e.g. for all electrochemical systems the cycle efficiency decreases with increasing charge/discharging power rate, whereas especially for thermal storage the stand-by losses are crucial for longer durations of energy inclusion. For the user of a storage system not only the storage capacity in the storage itself is important but also the net storage capacity which defines the useful output of electrical energy to the grid. Besides discounting the losses one must take into account that it is generally not possible for technical and/or economic reasons to exhaust the storage down to zero.

8.4 Storage technologies

Storage technologies can be distinguished according to Table 3 into three major groups with different features. Main characteristics and features of the different storage technologies are discussed below.

Table 3: Overview on storage applications and suited storage technologies

	X-Large Scale	Large Scale	Medium Scale
Response time	> 15 min	< 15 min	1 s -30 s [1)]/ 15 min [2)]
Typical discharge times	several days up to weeks	several hours up to 1 day	minutes up to a few hours
Typical storage capacity	100 GWh and more	10 GWh	< 100 MWh
Typical power	1 GW	1 GW	10 MW
Typical cycle frequency	few cycles/year	1 cycle/day	1 cycle/day or more
Storage technologies	Hydrogen based storage systems	Compressed air storage (CAES)	Batteries (Li-Ion, lead-acid, NiCd)
		Hydrogen storage systems	High-temperature batteries
		Pumped hydro	Zinc-bromine batteries
			Redox-flow batteries
Suited applications	reserve power compensating for long-lasting unavailability of wind energy	secondary reserve	primary reserve [1)]
		minute reserve	secondary & minute reserve [2)]
		load levelling	load levelling, peak shaving

There is over 90 GW of **pumped hydro storage** in operation worldwide, which is about 3% of global power generation capacity. Pumped storage plants are characterized by long construction times and high capital expenditure. Pumped hydro storage is the most widespread energy storage system in use on power grids and is commercially available from many manufacturers. However, a large percentage of pumped hydroelectric potential has already been developed in North America and Europe and the construction of new plants is getting more and more difficult, also due to an increasing ecological opposition. Typical applications of pumped hydro power plants are secondary and minute reserve, peak shaving, or load levelling and they have black-start capabilities. The typical efficiency range is 65-80 %, strongly dependent on the site. Recently developed motor/generators with speed control offer the possibility to participate in the frequency control of the grid also in the pumping mode – of course only if already running. Depending on the size of the upper and lower lakes, typical discharge durations realized today are in the range of a few hours. The power range is 10 MW to 1 GW and the time to full power is in the order of 90 s.

Although a huge storage capacity exists in Norway’s hydro power plants, only a very limited number is equipped with a pumping possibility today. Of course there is a high technical potential to convert these plants into pumped hydro power plants but for being used to satisfy the need in Central Europe it is not only sufficient to add just pumps but also to install additional turbines, pumps and penstocks. Furthermore, the corresponding power links (lines and sea cables) would be necessary for their connection. Also in Norway new overhead-lines are not welcome, especially when they are not needed for national power supply issues. Another hinder could be the possible influence on the Norwegian energy market which could entail a higher price level in Norway. Therefore only a limited contribution from Norway to Central Europe can be assumed.

Compressed air energy storage (CAES) has similar properties as pumped hydro, but with other geographic restrictions as the cavern leaching needs suited salt deposits in the underground. At the time being, only two plants are in operation worldwide. These existing **‘diabatic’ CAES plants** can be thought of as a gas turbine plant, where compression process and expansion process are temporally decoupled: excess electricity is used to drive turbo-compressors that fill underground caverns with compressed air (cooled down to ~50 °C). At times of peak load, compressed air is drawn from the cavern, then heated in gas burners and expanded in a modified gas turbine. As a drawback, the cycle still depends on a fossil fuel and also has limited cycle efficiency due to the waste heat emerging from the compression process. Improved implementation makes use of the gas turbine waste heat with the help of a recuperator in the flue gas path. However, the system inherent limitation of the efficiency remains. **Adiabatic CAES**, a novel concept, seeks to overcome these disadvantages by re-incorporating the otherwise lost compression heat into the expansion process and thus to provide a locally emission-free storage technology (no additional fuel is needed anymore) with a high storage efficiency. It thus needs a heat store as a central element of the plant. So far, adiabatic CAES are a subject of research, while diabatic CAES technology is commercially available from several manufacturers. The multitude of suitable sites for CAES is a beneficial condition for a broad introduction on the market. Previous studies show especially good technical and economic potentials in the Netherlands and in Northern Germany. A typical pressure is in the range of 6-10 MPa. For daily cycling the usable pressure swing has to be limited to approx. 2 MPa. The round-trip efficiency is in the range of 42-54 % for diabatic CAES and up to 70 % for adiabatic CAES are expected. Depending on the size of the cavern, discharge durations from a few hours up to a few days could be possible. The time to full power is in the range of 15 minutes which is sufficient for providing minutes reserve.

Hydrogen can be produced from electric power by high pressure electrolysers (pressures between 3 and probably 20 MPa). Different electrolyser technologies are under discussion. For efficient storage, hydrogen has to be further compressed before stored in underground salt caverns at a pressure of up to 20 MPa and above. As charging and discharging is slow, a pressure swing of about 2/3 can be realized. For high power levels the most efficient conversion back to electricity can be achieved in combined-cycle power plants. In the lower power range fuel cells can be applied. Round-trip efficiencies are expected to be in the range of 35 - 40 %. The achievable energy density of compressed hydrogen is more than a factor of 50 higher than the one of compressed air. The storage of compressed hydrogen in salt caverns being relatively cheap qualifies this technology especially for long-term storage of bulk energy to be reused during long-lasting unavailability of wind energy. Further research will be needed in the field of electrolysers and gas turbines suited for hydrogen.

Hydrogen offers also the possibility to be added at low concentration to natural gas (up to a few per cent). Thus the existing gas infrastructure (grid and storage) can be used and all the known gas-applications might be addressed. Another possibility under discussion today is the methanisation of hydrogen with CO_2. As this chemical reaction causes additional losses the round-trip efficiency of the storage process will be only in the range of 30 % when using this artificial methane for power production, even in high efficient combined-cycle power plants.

All these hydrogen based systems are currently considered to be the only technology being able to provide sufficient capacity for long term storage.

The **lead-acid battery** is one of the oldest and today still the most used secondary battery technology worldwide. Lead-acid batteries are commercially available from many manufacturers all over the world and there are also large scale installations in the 10 to 50 MW-class which have been in operation in the past 25 years. Their biggest advantage is the low cost compared to other battery storage systems. The typical efficiency range is 80-85 % (converter losses not included). The lead-acid battery is more a high energy technology rather than a high power technology which means typical discharge durations in the range of 1 hour and more. Discharge durations below 15 min are possible but generally make no sense as the available capacity decreases significantly with increasing discharge current rates. The lead-acid batteries suffer especially from their short life-time, limited usually to a few thousand of cycles and depending strongly on the depth-of-discharge (DOD).

Nickel-cadmium batteries are a very successful battery product from a technical point of view and it is the only battery technology that still features a good power capability at temperatures in the range of -20 to -40°C. Large battery systems built from NiCd batteries are in operation, similar to those for lead-acid batteries. The specific costs per capacity are significantly higher compared with lead-acid batteries, however they can provide a long cycle lifetime with more than 10.000 cycles at 80% DOD. The use of cadmium is critical and therefore, this technology is on the inspection list of the EU preceding a possible prohibition, which can only be impeded as long as there are no alternative storage technologies available. The efficiency of NiCd batteries is about 70 % (not including converter losses) due to the low nominal voltage of the basic cells.

Lithium-ion batteries have become the most important storage technology in portable applications (e.g. laptop, cell phone) as well as for mobile applications in electric vehicles due to their high gravimetric energy density. Also in stationary applications, they could be an interesting option because of their high power capability. Recent developments of larger cells for stationary applications underline the future potential of this technology. Discharge times of 15 minutes or less are possible. Different from other secondary battery technologies a large variety of material combinations are available for lithium-ion batteries. The efficiency is 90 to 95% (not including converter losses). The gravimetric energy density is superior to all other commercial rechargeable batteries in the capacity range of kWh and above.

Sodium-Nickel-Chloride- (**NaNiCl**, also called Zebra-battery) and **Sodium-Sulphur-batteries (NaS)** have a solid state instead of a liquid electrolyte like other batteries. To achieve sufficient ion conductivity and to transfer the active masses into fluid condition, an operation temperature of 270 – 350°C is necessary. When the battery is cooled down, charging or discharging is not possible anymore and there is the danger of cracks in the ceramic electrolyte because of mechanical tensions. For daily utilization, the temperature of the battery can be maintained by its own reaction heat with an appropriately dimensioned isolation. Thereby these batteries qualify for applications with daily cycling. The efficiency is 70-80 % (not including converter losses). High temperature batteries are typical high energy batteries.

In **redox-flow batteries**, the active material is made up of salt, which is dissolved in two different fluid electrolytes. The electrolytes are stored in tanks and are pumped, when needed, into a central reaction unit (stack) for the charge or discharge process. Similar to fuel cells the stack undergoes no physical or chemical change during the charge/discharge process. The size of the tank determines the energy capacity of the battery; the stack determines the power. Principally, this battery technology suits very well for a large-scale technical operation because the construction of bigger tanks can be done very easily and effectively. The system efficiency (including energy consumption of pumps, etc.) of most systems is in the range of 60 to 75 % (not including converter losses). Redox-flow batteries are a typical high energy battery and less suited for power applications with discharge times below one hour.

8.5 Economic assessment

When evaluating most suited storage technologies, it is necessary to define the boundary conditions in terms of power, energy, response time and capital costs precisely to achieve comparable results. Two classes of storage applications are discussed here with regard to suited storage technologies and cost estimations:

A) Long-term storage (500 MW, 100 GWh, 200 h full load, ~1.5 cycle per month)

B) Load-Levelling (1 GW, 8 GWh, 8 h full load. 1 cycle per day)

In the VDE Study “Energiespeicher für die Energiewende” a life cycle cost (LCC) analysis has been performed for different storage technologies with respect to the three application classes. Each application is defined by the required charge/discharge power, the necessary energy content (resulting in the effective gross energy content of the storage), the number of cycles per day and the required overall system lifetime. If a storage technology is not able to achieve the required system lifetime, the storage system or the relevant subsystems are assumed to be replaced and the costs are accounted accordingly. The LCC takes into account investment costs for the storage medium itself including the necessary auxiliaries and the power interfaces for charging and discharging, resulting in corresponding capitals costs. The lifetime - for some technologies depending on the cycle depth - is also taken into account as well as costs for buying electrical energy for charging and for the compensation of the overall losses. All calculations are based on a capital cost rate of 8%/year. For CAES systems only the new adiabatic technology is taken into account here. In the following, the cost figures are given as capital costs related to the systems electricity output.

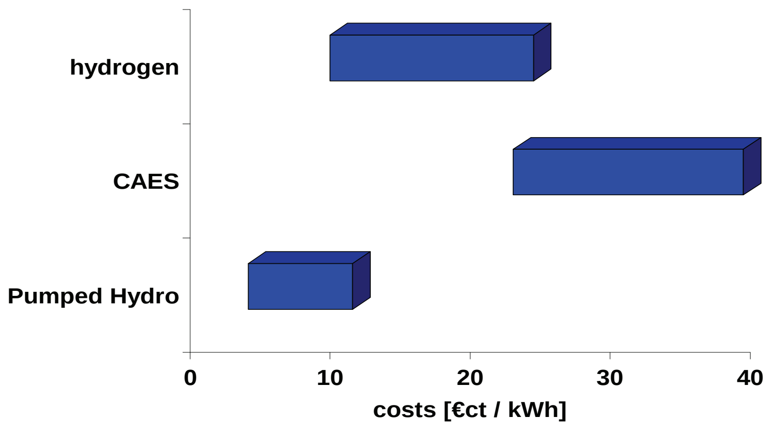


Figure 71: Comparison of storage systems for long-term storage (class A)

The width can be interpreted as “state of the art” (high value) and “achievable costs” expected in 5 to 10 years (low value). For the class A application (figure 71) hydrogen storage can benefit from low volume related costs due to its very high energy density compared to CAES. Pumped hydro storage systems could be used as long term storage at lower costs, but the technical potential for appropriate sites with large storage capacities is very limited whereas salt cavern for hydrogen storage could be made available in sufficient quantity in suited regions.

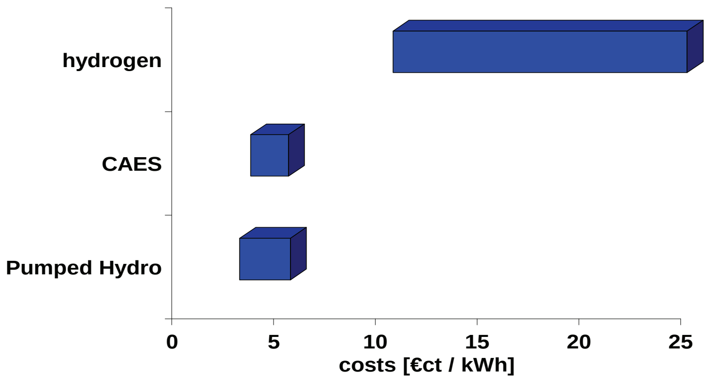


Figure 72: Comparison of storage systems for load-levelling (class B)

Class B is covered today by pumped hydro power plants, still being the most economical solution (figure 72). However, increasing the number of pumped hydro systems is limited by the lack of geographically suited sites and decreasing public acceptance. Compressed air stored underground in large salt caverns appears as an economic interesting and technically feasible alternative. Especially the new adiabatic CAES concepts show big advantages with regard to efficiency and ecological aspects. Battery technologies generally can be used for this application as well, centralized or decentralized. Here, the lowest costs are expected to be in the range of 8 to 12 ct/kWh. Although this is well above the costs shown in 2, it is necessary to take into account, that all battery systems can deliver also primary reserve due to their very fast response time to full power which is less than 10 ms.

8.6 Alternatives to energy storage systems

As mentioned above, beside the application of demand-side management measures the balancing between regions or even countries will be the first choice in order to cope with imbalances between generation and load. Even if grid enhancement or grid extension would be necessary, this is generally the cheapest and also the most efficient solution. Of course grid reinforcement cannot avoid completely the need for storage but may drastically reduce it.

It seems to be evident - at least for economic reasons - that it will not be possible to use the power from fluctuating RES to full extend. High power peaks with short durations need special consideration. It appears to be acceptable that these peaks could be cut off without important monetary losses. Thus also RES will need to participate in generation control in the future. In some countries, e.g. Ireland, the wind-turbines have to contribute to the primary control (positive and negative) already today. Furthermore, flexible conventional power plants will be needed which allow fast generation control in order to compensate the fluctuations from RES in the secondary control regime as well as for providing reserve power.

Chemical storage underground (e.g. hydrogen or methane) is regarded to be well suited for the balancing of longer periods. Nevertheless, chemical storage of excess power from RES suffer from the low efficiency of the transformation from power to gas and again back from gas to power as well as from the high investment costs of the plants. Therefore it will be a challenge to reduce the need for such transformation to a minimum. In future energy supply scenarios the focus cannot be limited to the power supply sector only but should include the gas and heat sector as well as the traffic sector. This will allow a more general optimization as it allows taking benefit of the specific advantages of the different systems, e.g. the large storage capacity already existing in the gas supply system. Taking into account that gas is mainly used for heat production, it appears to be evident to replace gas by electric heating during periods with excess power from RES using this excess power directly without any intermediate transformation. This approach is also called “virtual methanisation”: due to the savings of gas during periods with excess power there will be even more gas in the system as when using the same excess power for the production of gas via electrolysis followed by a real methanisation process. The gas, saved during the excess periods can be reused for heating or power generation during periods where there is a lack of power from RES. The retrofitting of a conventional gas boiler to become such a hybrid heating system is low cost, especially when compared to electrolysis and methanisation.

9. Option for future decentralized micro grid energy structures

9.1 Driving factors

According to the initiatives of the European Commission and the Strategic Energy Technology Plan (SET-Plan) [9.1] until the year 2020 about 20% of the European electricity demand should come from wind energy and about 15 % from photovoltaic. The “Energy efficiency – Smart Cities Initiative” of the SET-Plan has the aim to reduce the greenhouse gas emissions by 40% through these measures and to develop zero-energy buildings in different climate zones, especially by RES heating and cooling in cities and their integration in energy efficient buildings. The so called “smart cities”, “smart grid” and “micro grid” technologies will enable the “energy active” settlement structures.

Also seen from the traditional electrical energy system, strategies towards energy efficiency and smart cities are necessary. As the main energy sources of the future – wind and PV – are limited, efficiency forms the precondition for the transition to RES supply. Seen from the electricity grid, it will not be possible to reinforce the existing grid or to build higher voltage level transmission systems in time. According to the shorter time of usage of onshore-wind (1.700 to 2.300 h/a) and PV (800 to 1.300 h/a) much higher generating power must be installed compared to run-of-river hydropower (4000 to 5000 h/a) or thermal power stations (up to 8000 h/a) leading to “power-oriented” energy systems.

A second problem represents the fluctuating generating scheme of RES, which necessitates storing of the energy and balancing by backup supply. Figure 73 shows that the pumped-storage hydro plants in EU-27 + will be doubled in power until 2020 but their relative power, related to the installed RES will go down by 30%. Also the energy to be stored is too small, according to the volume of the upstream and downstream water reservoirs. In EU-27+ at full turbine power in about 7.5 hours all upper reservoirs will be empty, which means, that only short term storage capacities in EU-27+ are available.

The energy strategy of the future must be to consume as much renewable energy where it is generated but not to transport in ultra high voltage grid over long distances and not to store long term in very voluminous reservoirs. The existing transmission and distribution grids have to be reinforced and the thermal and hydraulic power plants are still needed for security of supply. This aim of integration of new and cooperation with existing system is valuable seen from costs, environmental impacts and acceptance of population.

The micro grid technology seems to be favorable, because it enables a local energy storage in the electrical vehicle or in stationary batteries in the buildings, a grid control and energy management, to balance the energy demand according to the RES generation and to make the energy supply of settlements more reliable and more independent of emergency situations in the overlaying distribution and transmission grid.

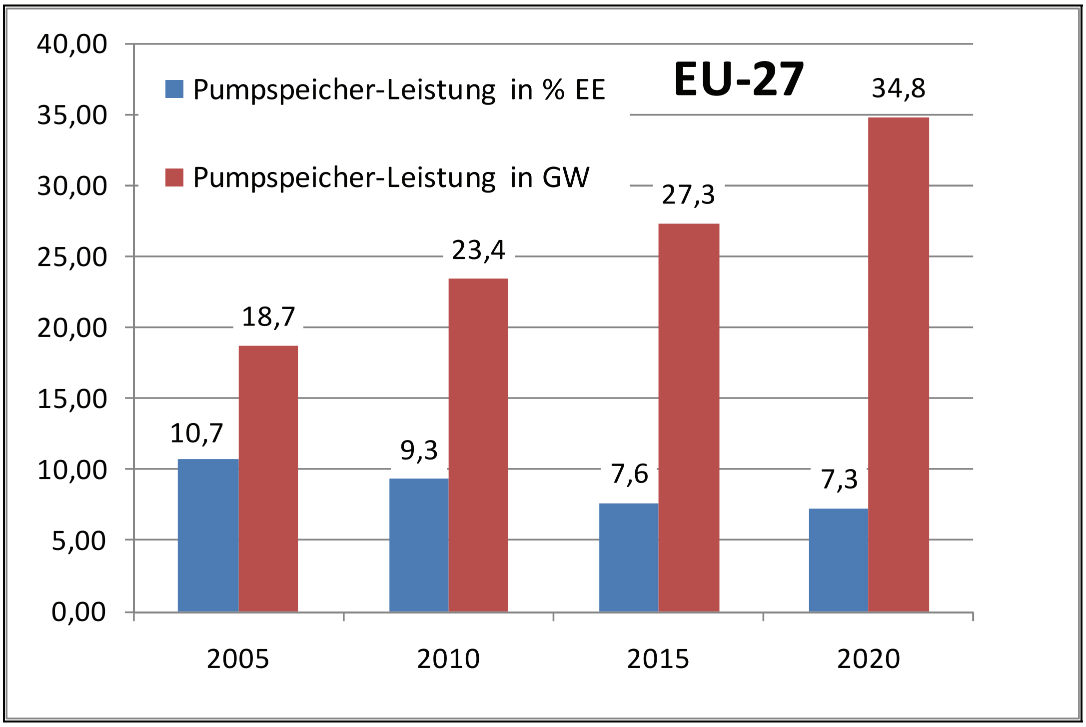


Figure 73: Electric power of pumped storage hydro plants in GW and relative power in % related to installed RES (NREAP, [9.2])

The existing transmission and distribution grid are still vital important, as there are longer periods without sufficient generation of wind and PV. During this time the traditional thermal power stations have to deliver the missing electrical energy. But as they are only used for residual supply their emissions will be reduced significantly. The transmission grid itself helps also to exchange renewable energy between regions and thus to reduce the demand of storage capacities.

9.2 Photovoltaics

Photovoltaic is now under rapid development of installations (figure 74). Today PV systems show costs of about 2.5 €/W_p and reach by this the grid parity, which means, that the electrical energy of PV is competitive to the utility price.

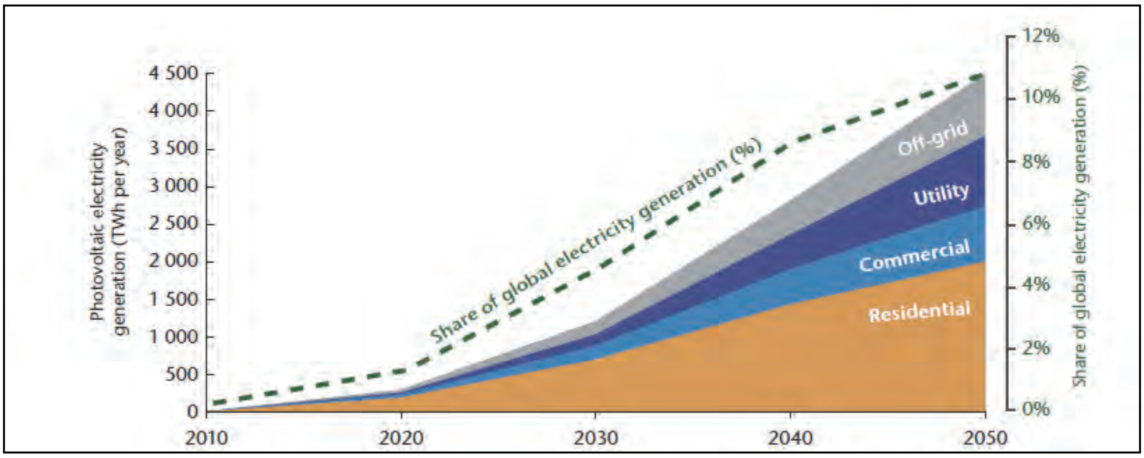


Figure 74: Evolution of PV by the end-use sector ([9.3] IEA)

Seen form the costs PV is getting competitive in the private sector and here most of the capacities are installed, necessitating smart grid and micro grid technologies.

A doubling of the production capacity results in a price reduction of about 20%. So the residential sector is the first which will show installations of large capacities of PV. It can be foreseen that until the year 2020 the specific price of PV installations may come down to 1 €/W_p and so PV will also be competitive to classical thermal power stations and will have also large installations in the utility and commercial sectors.

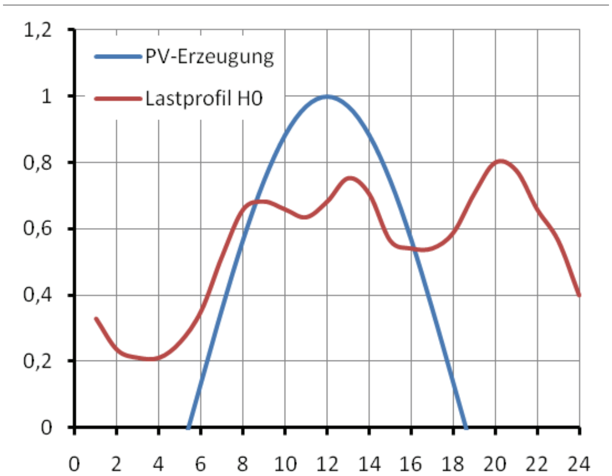


Figure 75: Typical profiles PV generation in an energy active settlement

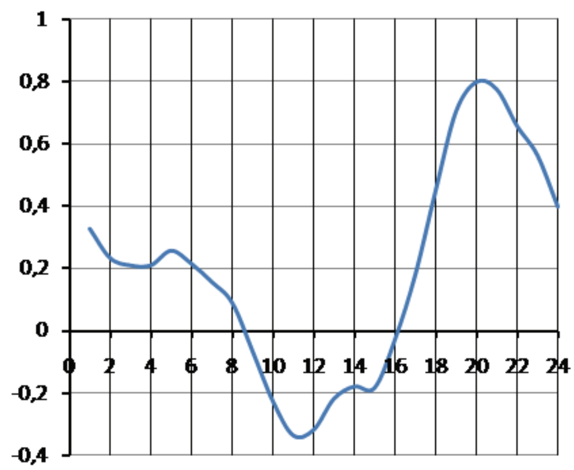


Figure 76: Residual balancing power to the grid

Figure 75 shows an energy active settlement with PV generation on a summer day and the standardized load profile of a household. The difference between generation and load represents the balancing power, going at noon to the grid and coming in the morning and evening from the grid. Especially in the evening high gradients in power generation are necessary. This necessitates flexible conventional power generation with the ability of high generating gradients.

One severe problem of PV is its synchronization by the solar radiation. So in the morning it starts, at noon high over production is possible and in the evening reduction by sun set coincidences with high electricity gradients of demand.

9.3 Solar Thermal

Solar thermal installations are very valuable for warm water heating and water boiler recharging for heating purposes. About 85 % of warm water demand can be derived from solar thermal collectors over the year and thus saving electrical energy. Solar thermal application for heating purposes is difficult, as during the main heating period in winter the solar radiation is low and additional heating equipment is necessary.

By solar thermal energy for shower, hand washing and dish washing in a household about 1000 kWh per annum of electric energy can be saved in Central Europe.

9.4 Micro grid management

The decentralized generation in energy settlements should be linked to a micro grid management. The following arguments necessitate this procedure:

- PV generation in settlements forms a form of renewable generation which is synchronized. The grid capacities per household are limited by a value of in the range of 2 to 5 kW. The maximum statistical load of a household is about one kW but with PV the feeding back value could exceed this value significantly. As investments in distribution grid represents about 80 to 90% of all investments, it is not economic to reinforce it for a usage time of only 100 to 150 h/a.
- Hydro storage capacity in the transmission system is far too small for extensive PV installations and grid capacities are too small for transport of large amount of PV energy. Local consumption seems to be better than wasting the PV energy.
- Micro Grid management has the following functionalities:
    - Demand Side Management (DSM) to synchronize local demand to local generation.
    - Energy Storage Management (ESM) to store as much of electricity locally for mobility in electrical vehicles or end-use in local batteries for small scale energy applications as there are illumination and ICT.
    - Supply Side Management (SSM) to use as much of balance supply if demand and storage abilities are exceeded and no additional energy application (e.g. resistive heating, heat pumps, synchronized clothing or dish washing) are available. In case of over generation temporary switching off is necessary.

- o Grid control under insulated operation and black start ability form further management functions. Herewith the micro grid can overcome emergency or blackout situations in the superposed transmission grid.

9.5 Strategic analysis of micro grids

Micro grid technology can be linked in the future with efficiency in end-use, local renewable generation, electrical mobility with grid balancing grid-to-vehicle (G2V) and vehicle-to-grid (V2G) and grid management for improvement of supply security and blackout resistivity. It can thus reduce to some extend the need for very big grid and storage extensions and balance the micro grid in a way, that the existing and available grid and storage capacities, which are the limiting factor of the renewable energy system, can be used without significant emergency situations.

The micro grid technology itself forms a valuable complement to the existing transmission and distribution system and the thermal power stations, which are still necessary because of the fluctuating characteristic of the RES like wind and PV. The existing T&D system forms in future a security barrier for uninterrupted supply, system control and ancillary services. In the long range it must be converted to a highly flexible generation and transmission system, which supports RES development.

10. Integration of renewables, need for the enhancement of system flexibility

During the transformation phase into predominant renewable energy supply the European electricity sector faces many challenges. One of them is the integration of a quickly increasing share of renewable energy in the electricity generation-mix. The volatile feed-in from the solar and wind power plants impacts the stability and reliability of the grid operation and could develop to a serious issue of secure European energy supply. For the reason that renewable energy sources enjoy a priority in the grid feed in, the periods of grid-oversupply, as well as of deficits to cover the demand can be anticipated. In regions with high shares of renewable generation, time-periods with local energy and capacity oversupply can be observed already today. The currently mostly applied approach to handle this issue is the cutback of the renewable feed-in during the time of oversupply. With an increasing amount of generation based on wind and solar capacity the waste of energy is not reasonable due to the economic and ecological reasons. The “free” energy should not be wasted, but if possible, transmitted to regions, where it could be consumed. A possible alternative to the simultaneous generation and use of electricity is the storage of excess electricity and its later utilization during the time of appropriate demand.

Thermal power plants, historically developed and used for strictly defined operational conditions will be prospective facing different requirements. Two principal and opposite situations for their operation can be expected. Fluctuating feed-in will be in fact depending from the future weather conditions, but simply due to the quickly increasing capacity of the solar and wind capacity, the time periods with load oversupply will be occurring more and more frequently. In those periods thermal power plants and to some extend also storage facilities will have to take over the load control function and ensure the stable grid operation. In extreme situations, the thermal power plants won’t be needed at all and will have to be disconnected from the grid supply. Nevertheless, even opposite situation will have to be managed, where the grid feed in from renewables completely fails to appear. In these relatively improbable, but possible time periods the thermal plants will be required for the provision of the load control and backup power, at least as long as sufficient storage capabilities won’t be applied.

To ensure the indispensable security of supply during each weather conditions, the enhancement of the flexibility between the generation and consumption will gain a crucial importance. According to the different circumstances in European countries, which include diverse climate conditions, generation mix, the composition and flexibility of the thermal fleet, grid strength and density, as well as demand-structure, the dimension of over- and undersupply will be occurring in diverse patterns. Under consideration of few essential drivers: on the one hand of the projected share of the volatile feed in- on the peak-load demand, on the other hand of the shares of the flexible thermal- and pumped-storage power plants, the following figure has been created. It indicates for selected European countries their need for the improvement of the system flexibility in the perspective of approximately next ten years.

With an increasing share of the fluctuating feed-in and with a decreasing share of the flexible capacity in the country, defined as capacity of gas turbines, combined cycle power plants, reciprocating engines and pumped storage plants, the need for the enhancement of the flexibility along the entire supply chain rises. It doesn't surprise, that countries with ambitious targets for the expansion of renewable energy sources, which possess a large amount of quite old and inflexible steam power plants demonstrate the highest need for action to improve their system-flexibility. An exceptional position with share of renewable capacity exceeding the peak demand and with high amount of old steam power plants can be observed in Germany. Also United Kingdom, Denmark and Greece will probably have to put special efforts for the enhancement of their system flexibility

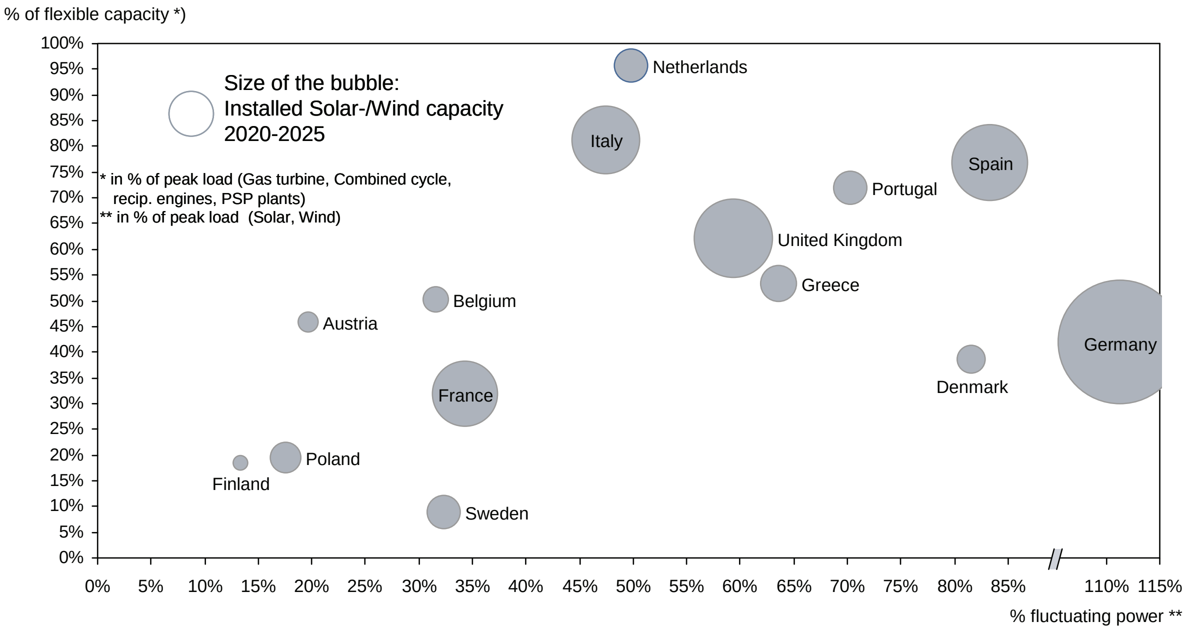


Figure 77: Need for action for the improvement of the system-flexibility in selected European countries in the time period 2020-2025

10.1 Scenario Germany

The recently published VDE Study „Renewable energy needs flexible power plants: scenarios until 2020" [VDE 2012] is good suited to recognize the most important correlations of the renewables-integration into the supply system also in Europe.

To assess the impact of renewables-feed-in, few essential assumptions for the system modeling have been made, i.e. the mix of electricity generation and power capacity changes based on the assumption, that the renewable share in generation mix doubles from 20% in the year 2011 to 40% in the year 2020. The thermal power capacity changes due to already decided actions like phase out of nuclear power or anticipated retirement of conventional units and construction of new power plants. For the modeling of the wind and solar feed-in typical, historical weather patterns in a 50x 50 km cell size have been used. The PV capacity rises from 27 GW in 2011 to 60 GW in 2020, wind capacity from 29 GW to 58 GW respectively. The electricity consumption and load curve do not change until 2020. The pumped storage capacity increases from the current 7 GW by 1,5-2 GW. The mobile and stationary storage capacities increase slightly and the measures from the demand side management (DSM) or demand response (DR) do not have a systemic relevance until then. The grid has been assumed as an ideal grid without any restrictions in the transmission and distribution of electricity

One of the essential results of the VDE study is, that during the transition period to the full renewable energy supply patterns two parallel generation systems: renewable and fossil/nuclear have to be maintained, mainly due to the lack of sufficient storage capacity [Pyc 2011]. During the simultaneous operation of those two systems multiple technical, as well as economic challenges for the stable grid operation emerge. The volatile solar and wind energy feed-in shows stochastic behavior, which is a crucial characteristic for the future operation of thermal plants and at least for the reliable system operation. Longer periods of non-available wind and solar generation can appear. In such periods thermal power plants as backup power and in load control function will be needed, at least as long as sufficient storage capability won’t be available. In such scenario, the flexible thermal generation will be developing more and more to the one of the key enabler of a successful system transformation to full renewable supply.

One of the suitable flexibility-criterions for the sharpening requirements for thermal power plants is residual load curve. It reflects the hourly load fort the „non-must run“ plants and is expressed by the difference of the hourly grid load and feed-in from „Must-Run“- plants. „Must-Run“-means plants which enjoy the priority in the grid supply.

As it can be observed on the following figure, the simulated hourly residual load curve for the year 2020 fluctuates strongly, showing positive peaks in the range of the maximal load in Germany (low feed-in contribution of renewables) an negative peaks at 20 GW (high feed-in contribution of renewables).

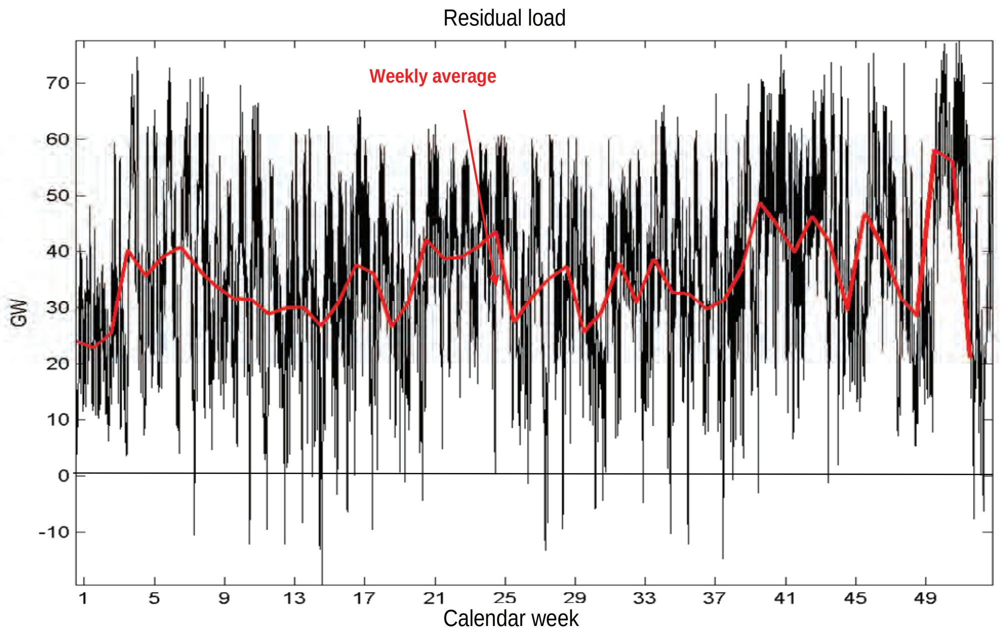
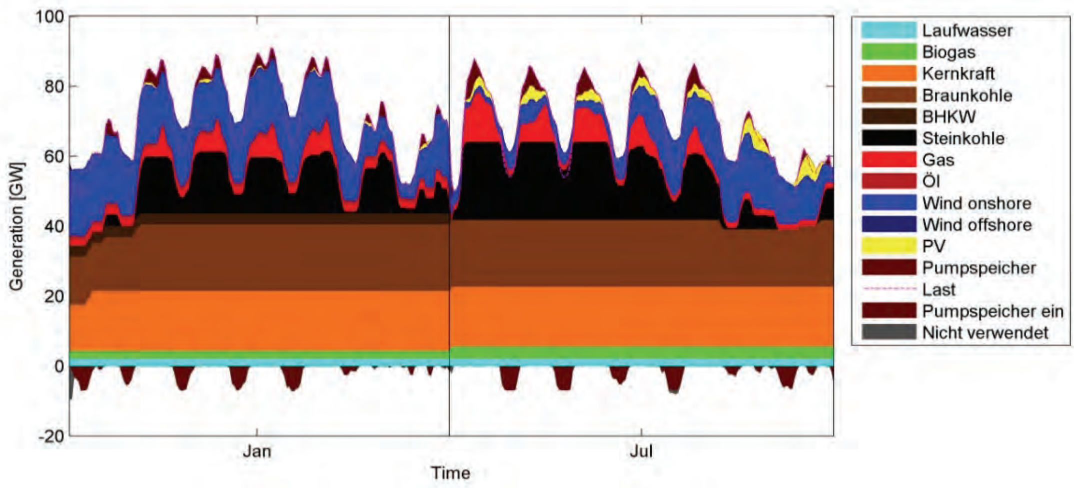


Figure 78: Residual load in Germany, 2020, Scenario with 40% share of renewable generation [VDE 2012]

Due to the temporary grid oversupply different circumstances emerge. On the one side, wind power alone might be able to cover large parts of the entire German load during the wintertime. Nonetheless, despite the potential oversupply by renewables, the projected and feared transmission deficits from the north to the south of Germany won't allow to transport the available wind-power to south Germany and in the consequence to decrease load or even shut down the thermal power plants. On the other side, during the sunny weather periods daily high feed-in peaks, especially in south of Germany will arise They will require in addition to the required grid extension more hourly storage capacities to accommodate the high daily PV- and possibly wind feed in. It is already today foreseeable, that the pumped storage plants alone won't be able to manage a high mismatch between generation and consumption and will have to be supported by flexibility measures in the demand side. These examples illustrate the urgency of the appropriate grid- and storage-capacity extensions, as well as DSM/DR implementation to accommodate the quickly increasing shares of renewable power.

The simulation of the future supply (figure 79 b: July) shows exemplary, that the total available capacity from renewables and thermal fleet during the summertime in Germany in the year 2020 day can exceed the load by 100 %.

a)



b)

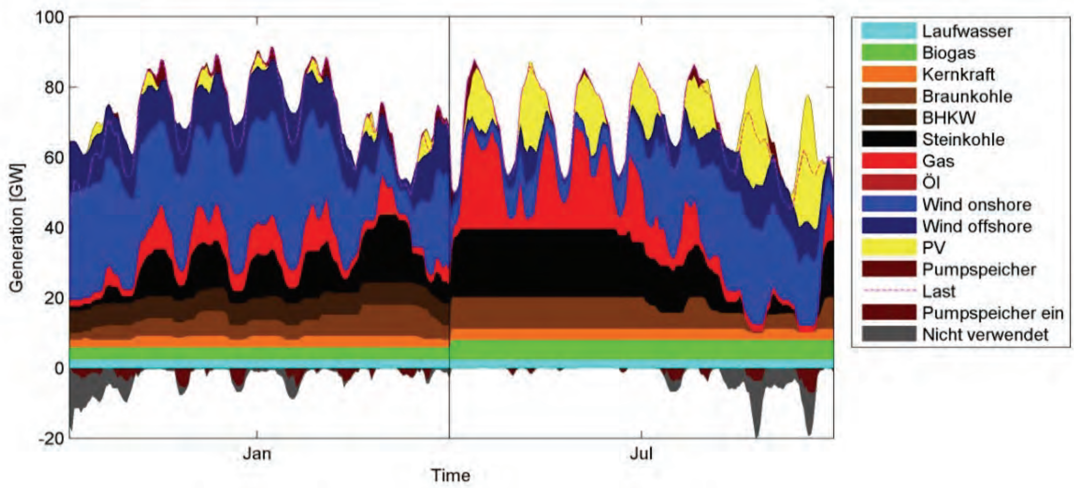


Figure 79: Energy mix for 2 selected weeks. a) Scenario 2009, b) Scenario 40% of renewable generation [VDE 2012]

The simulation for the wintertime shows once more a high feed in by wind plants. Nevertheless opposite situation can occur, with no feed in during windless and cloudy days. As already mentioned, in such times, full load coverage by conventional power (supported by available storage capacity) will be required.

The demonstrated examples indicate the urgency for the enhancement of flexibility along the entire supply chain. Shouldn't satisfying solutions be founded and implemented, an increasing waste of renewable energy would be an unavoidable consequence.

Another important aspect of the renewable integration is holding of available conventional thermal capacity for these time periods, where the renewable feed-in doesn't happen. It is in absence of sufficient storage facilities obviously a necessary, but quite expansive practice to ensure the high level of security of supply. Some significant challenges for the operation of thermal plants can be observed already today. For example: decreasing load factors for do not provide sufficient economic base for the investments in new, in some cases even for a durable operation of existing plants. In this manner, the currently existing and strongly "energy" related market design, which is mainly based on variable costs ("merit order") and on load control payments (limited to 1 hour) meets his limits. It seeks supplementary measures, mainly to consider the value of load control function, ancillary services and availability features of the plants. In addition to the shrinking load of thermal plants several other factors impact the future economics of operation of the thermal plants, among others: number of starts and shut-downs and height and frequency of load-gradients. In this regard, the following figure provides a 2020 outlook in the 40% renewable generation scenario and compares the results to the situation in the year 2010.

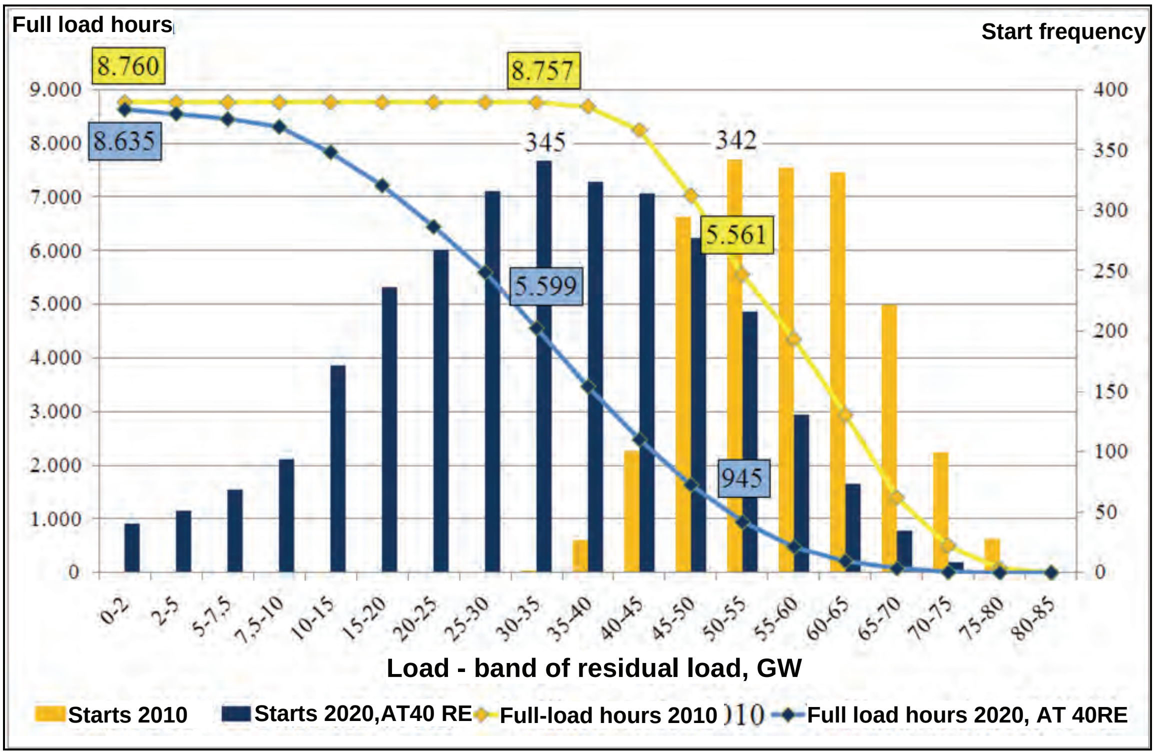


Figure 80: Full load hours and number of starts for different bands of residual load. Scenario with 40% of renewables in the generation mix. Comparison 2010- 2020 [VDE 2012]

Significant changes can be observed. In particular, whereas in the year 2010 the up to 35 GW can be run in the typical base load operation mode, in the year 2020 app. half of this capacity reaches high load factors. The utilization of thermal plants decreases significantly, comp figure 79.

Besides shrinking load factors, the number of necessary starts changes as well. Whereas on average 20-25 GW of thermal capacity starts today daily, this number is projected to increase up to 35 GW in 2020. Moreover, a further consequence of the integration of renewables is the changing magnitude and distribution of the load gradients, which thermal plants are facing to properly balance the system. On the figure 81 similarly to the chart 4 respective changes of residual load ramps between the year 2010 and 2020 are presented. During the year 2010 (16% of renewables in the German generation mix) the hourly load changes were mostly varying between +/- 2 GW. The highest load change was achieving +8/-6 GW/a. In the year 2020, hourly load change of +/- 10 GW/a could be occurring already once a day. Less likely, but even significantly higher changes in the range of +/- 14-12 GW/a might be observed as well. The amount of hours with no residual load changes (0 GW/1h) decreases from 20% to 10% of the yearly hours (8760h). Regarding residual load changes over 3 hours, much higher magnitudes of up to + 30 GW/3h can take place app. 10 times a year, which is 1/3 higher than in 2010.

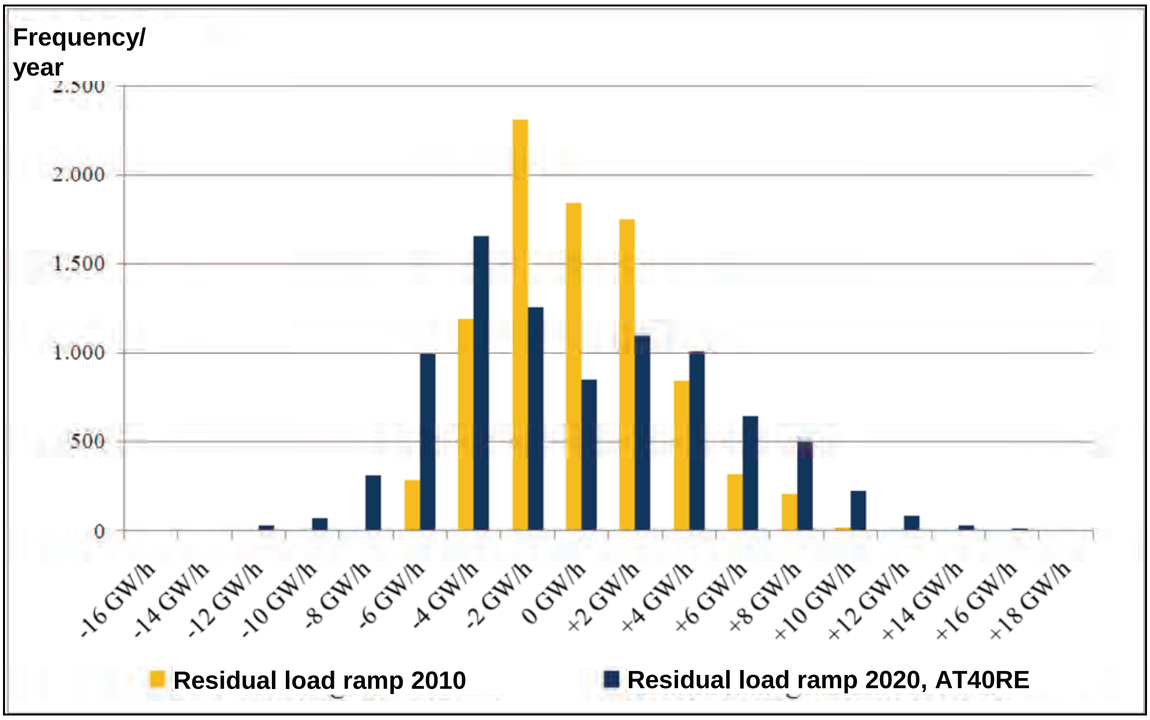


Figure 81: Gradients of the residual load changes over 1 hour, comparison of the year 2010 and 2020: scenario with 40% share of renewables in the generation mix, [VDE 2012]

Summarizing all the described effects the high volatile feed in of wind a solar power, the thermal plants will be facing more and more fluctuating residual load, compare figure 78 and as consequence their number of starts and shut downs, as well as the magnitude and frequency of load gradient will increase. The technical and economic consequences for the plant operation and the lifetime of high thermally stressed plant components might be serious. .

In the described and specific example for Germany principal correlations of renewables-integration into supply systems can be clearly recognized and probably extrapolated to those regions in Europe, which face similar challenges with integration of stochastic grid supply. In the context of the absence of economically viable, large-scale storage, the burden of maintaining system reliability will at least fall mostly on the flexible operation of thermal generation units such as coal, natural gas and nuclear generation. However, the ability of these plants to operate flexibly is limited by both physical plant constraints and economic profitability considerations Nevertheless, the specific and detailed questions, how the deployment of large-scale renewables will be affecting conventional thermal plants and the limits of their physical and economical capabilities for specific accommodation of volatile feed in, will require further deepening studies.

10.2 Options for integration renewable energy and enhancement of the system flexibility

The challenges to integrate increasing amount of volatile renewable energy indicate needs for specific actions to address the issues of the future operation of the grid and thermal power plants. Moreover, the consumption side seeks practicable and economical ways to contribute to the system flexibility as well. Disregarding the emerging challenges multiple measures have been identified and could be applied already today to address the necessary accommodation of volatile renewable energy feed in. Despite possible solutions technical and economical multiple hurdles have to be overcome, as well as appropriate business models have to be developed and implemented yet.

The enhancement of the system flexibility can take place at singular places of the supply chain and various options between generation and consumption can be applied to respond to the challenges resulting from accommodation of volatile feed in, figure 82.

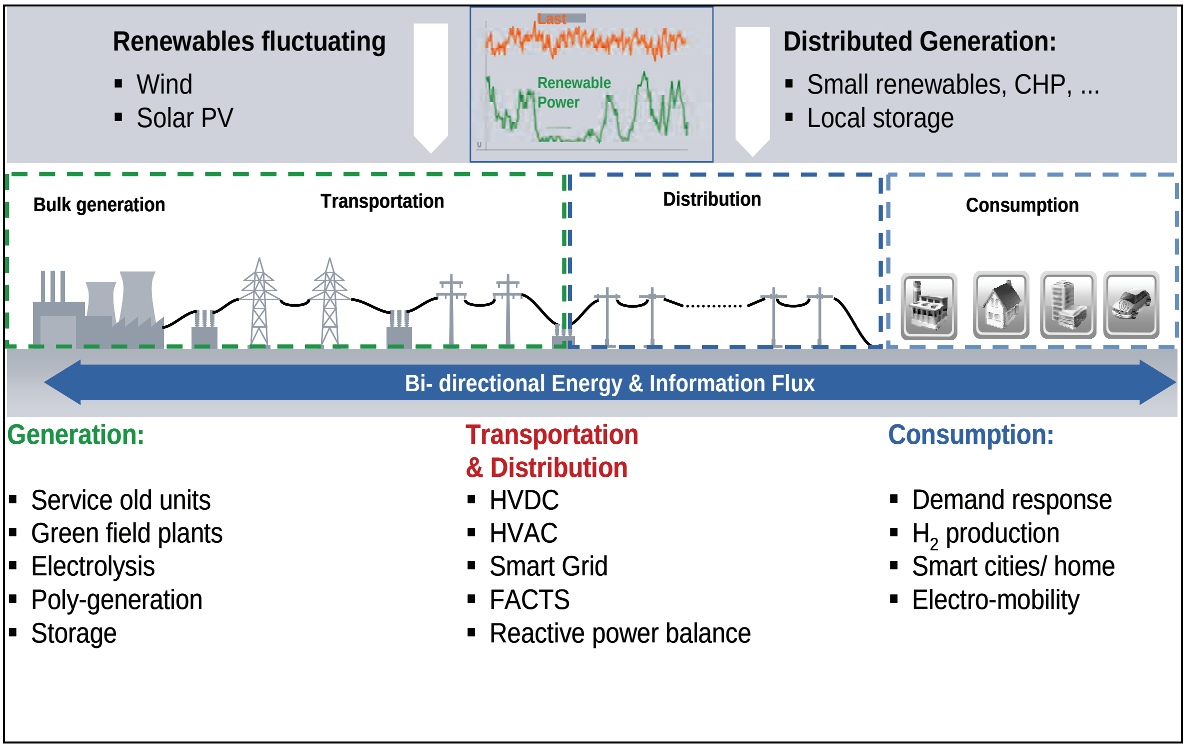


Figure 82: Opportunities for the enhancement of the flexibility in the electricity supply

The identified measures can be grouped as follows

- **Improvement of the flexibility of the power plants** →: control the load and provision of the backup power, balance and compensation of outstanding renewable feed in
- **Reinforcement and expansion of the infrastructure for the electricity transmission and distribution** → enlargement of the generation and consumption regions
- **Application of storage and demand side management (DSM)-, as well as demand response (DR)** → time shifting between the electricity generation and consumption.

It would go too far at this place to assess all those options in necessary details. Nevertheless, the technologies, which enjoy a special attention as key enablers during the integration of large amount of renewable energy in Europe is electricity storage. Comprehensive information about storage technologies can be found in the chapter 8. At this place we restrict further comments to the good prospects to use chemical compounds for electricity storage.

Due to their high chemical bond energy multiple hydrocarbons offer interesting opportunities to accommodate high amounts of electricity. The well-known electrolysis should be the starting point for the following synthesis of various hydrocarbons by use of H2, CO2 and appropriate catalysts. The simplest product in this ‘poly-generation” approach is the gaseous Methane. From this starting point even liquid products, like Methanol, Ethanol or Diesel can be synthesized and used as storage media or energy carrier. To demonstrate the high storage capability of the hydrocarbons we have created a hypothetical cube containing the same amount of energy, which can be approximately generated during one hour sunny and windy noon time by 1200 GW photovoltaics and 730 GW wind, which are projected in 2050 in the HiREN scenario of our study

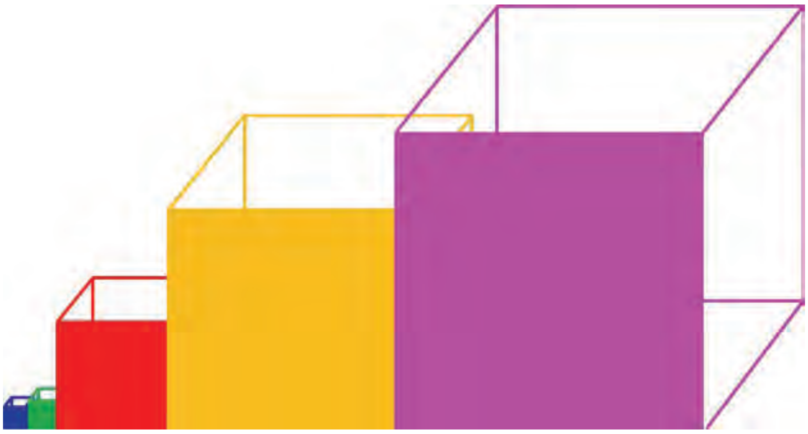


Figure 83: Length of the edge of a cube containing an energy equivalent of 1 h generation from wind and solar power in HiREN scenario in 2050.

11. Scenarios for the future power demand and generation mix in EU27+

Three scenarios were developed in order to have a clear understanding of how the power demand (s. chapter 5) can be satisfied by which generation mix. The scenarios describe the mix of generated electric energy and installed power to produce it with regard to the primary energy resources like fossil, renewables and nuclear, it calculates the greenhouse gas (GHG) emissions and it estimates the investment costs for erecting the necessary power plant capacities to produce the electric energy as estimated. One scenario just carries forward the actual trend. In the following it is named **TREND**. The second scenario is conservative with regard to the reduction of the GHG emissions compared to the EU reduction ambitions and with regard to the increase of the usage of renewables for the generation of electric energy. It is called the **LoREN** scenario (low amount of renewables). The third scenario takes a progressive approach in using renewables and in the reduction of the GHG emissions. This is the **HiREN** scenario (high amount of renewables).The assumptions for developing these scenarios are described below.

11.1 Methodology and data sources

The starting point for developing the scenarios is a profound estimation of the electricity consumption in the next decades until 2050. In chapter 5 this demand estimation is explicitly described for a conservative approach and a progressive approach (figures 23 and 24). Both show for 2050 nearly the same total consumption but with big differences between the sectors. The assumptions which led to the calculated demand for industry, transportation, households and services are also described in chapter 5. For the further scenario calculations the progressive demand estimation figures will be used. (Although the two demand approaches are quite different in detail the result in TWh´s is nearly the same: while the assumption for the efficiency improvements is much higher in the progressive than in the conservative approach the demand for new application like e-mobility, heat pumps, etc. is also estimated on a much higher level in the progressive approach. Therefore, both trends do nearly compensate each other with the result that the estimated electricity demand in 2050 is practically the same in both demand calculations). Finally the generation mix of the scenarios is computed such that it balances the estimated power consumption.

All past and actual data which are used for developing the scenarios such as installed power capacities, generated electric power and used primary energy resources are from EUROSTAT. The latest data are from 2008. All scenarios will fulfil the **current** agreed EU goals with regard to the reduction of the GHG emissions and the increasing use of renewables for power production.

Since the scenarios include massive power capacities of volatile renewables like wind and photovoltaics (PV) there must be build backup power capacities of the same order of magnitude. It is assumed in this study that the backup for the volatile renewables comes mainly from fossil power stations – typically gas – and only a very minor part from storages like hydro pump storages. In the public there are countless discussions on the development of huge storage capacities but until today no realistic approach or even development can be seen. Therefore for the time being we still have to develop realistic scenarios with fossil power station backup.

11.2 Main assumptions

In order to develop the three scenarios numerous assumptions had to be made. The main assumptions are as follows:

- The **TREND** scenario is just putting forward the actual trend. Fossil and nuclear power plants capacities will slightly increase while new renewable power stations will generate most of the power which is needed for the consumption increase.
- the CO2 resp. GHG reductions rate is assumed to be -60% in the **LoREN** and -80% in the **HiREN** scenario in 2050 compared to 1990
- the renewable capacities will produce 50% resp. 80% of the electricity in 2050
- there will be no use of uranium or coal as primary energy resources in the **HiREN** scenario. In the LoREN scenario their use will be reduced by 50%.
- In **LoREN** carbon-capture-and-storage-technology (CCS) will be applied to fossil power plants to filter out the CO2 from of the combustion gas.
- since the EU27+ will eventually work like a big common electricity market there will be no substantial power exchange with countries outside the EU27+.
- to calculate the needed investment costs the 2011-prices for power plants are applied. (It would not be a good idea to estimate the price development for the next decades. This is practically not possible.)
- the life cycle of power stations is assumed to 40 years for fossil, biomass and nuclear power plants, 80 years for water and 20 years for wind and PV power generators.

11.3 The LoREN-Scenario

As result of the projection laid down in chapter 5 the **tota**l electricity consumption (=net consumption + transmission losses + utility own demand) will rise from 3600 TWh in 2008 to 4950 TWh in 2050. So the generation has to follow in production to the same amount of electric energy.

The main objectives for the LoREN scenario are the reduction of the GHG by 60% compared to 1990 and to build up renewables power stations for electricity production to a share of 50% of the overall production. All coal power plants should use CCS technology to avoid CO2 emissions to the atmosphere and the nuclear power station capacity is cut by half partly due to the German exit from nuclear generation and some followers.

Applying that to the power plant mix the generation will come from renewables by 51% (see figure 84). 16% will be generated by coal, 20% by gas and 9% by nuclear power plants. In 2008 the relations were 22%, 25%, 21% and 26%, the rest comes from oil and others.

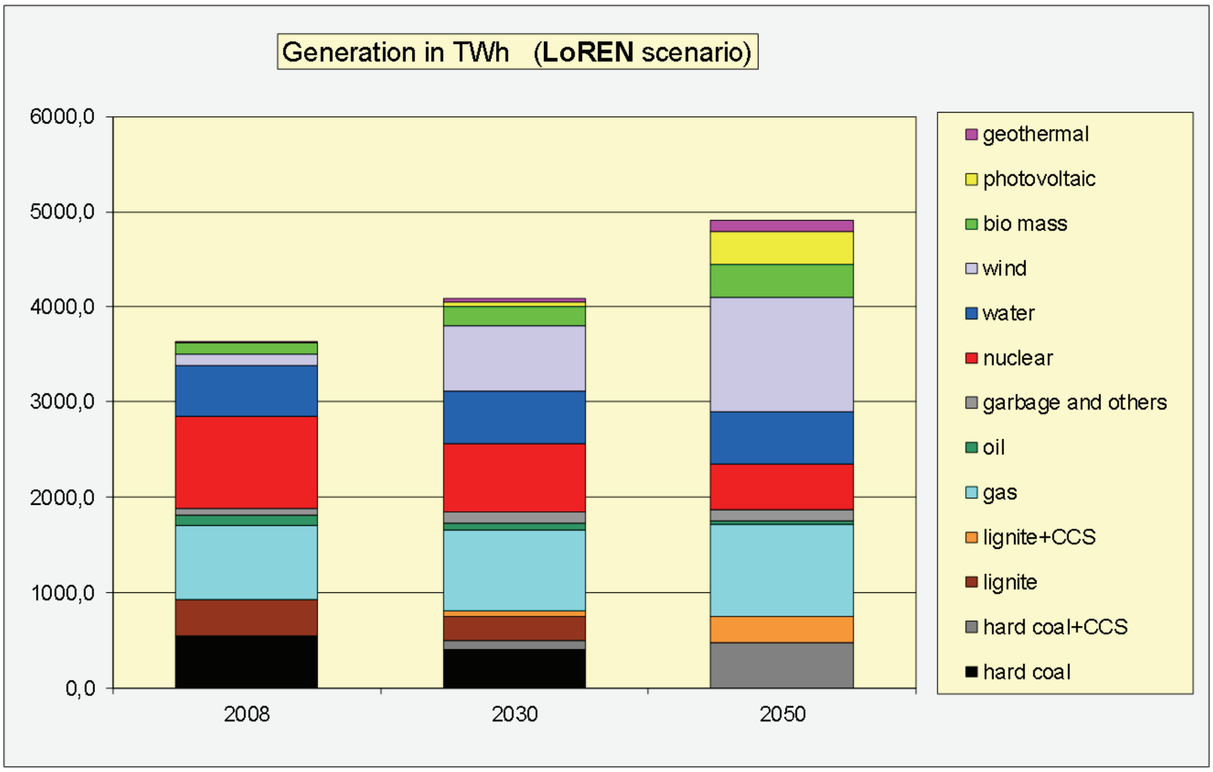


Figure 84: Generation mix in TWh in 2050 for EU27+ (LoREN scenario)

Quite different is the change of the relations for the installed power. In 2008 coal, gas and oil contributed to the installed capacity with 52% (15%, 21% and 16%). Nuclear had a share of 15% while the renewables including water contributed 31%. In contrast to that numbers of 2008 the situation in 2050 will be very different. The fossil power plants will have share of 33%, from which 17% are only for stand by purposes to back up the volatile renewables! The installed nuclear power capacity is shrinked to 4% and the renewables jump up to about 60% of the installed capacities with 10% of water power plants, 25% of wind and 21% of photovoltaic power stations. The rest will be biomass or geothermal power stations. In absolute numbers the installed power capacity would rise from 885 GW in 2008 to 2150 GW in 2050, an increase of nearly 300%! (see figure 85).

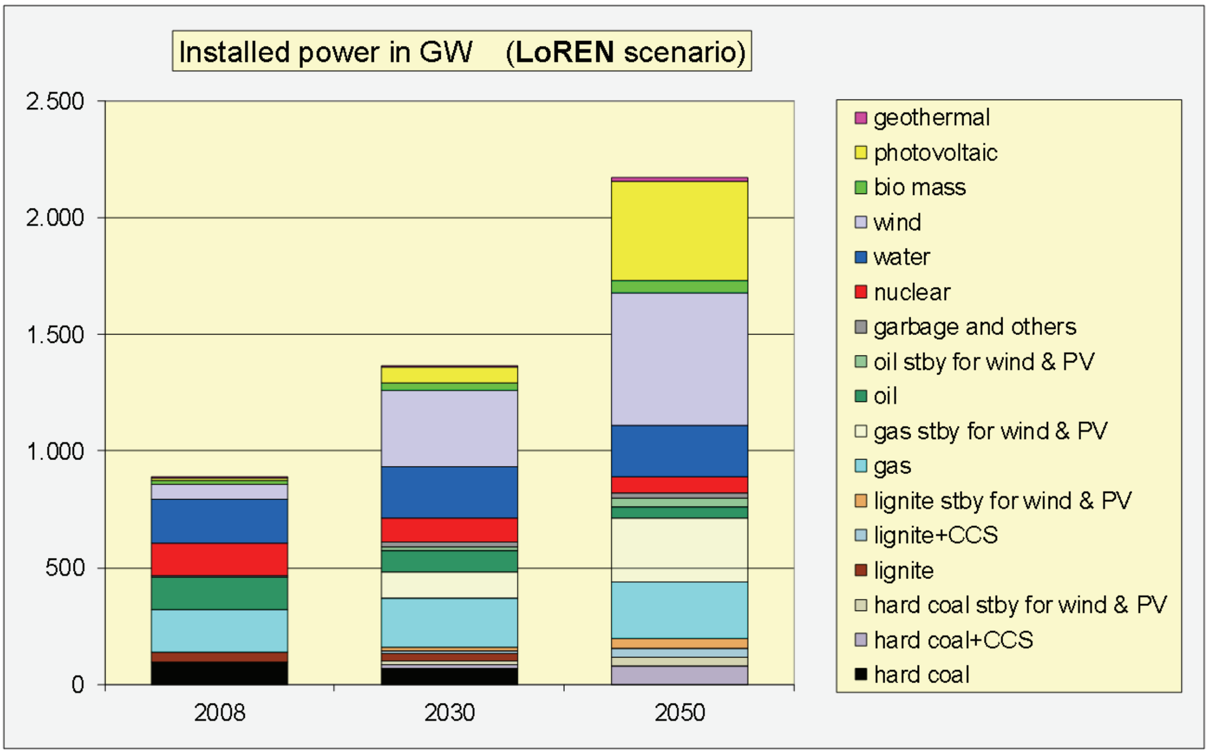


Figure 85: Installed Power in GW in 2050 for EU27+ (LoREN scenario)

The increasing use of renewables for electricity production and the application of CCS technology for coal power station will reduce the GHG emissions by more than 60% compared to 1990. Figure 86 shows the reduction of the emissions of the different fossil sources. If CCS technology would also be used in gas power plant than the CO2 emissions could be reduced to nearly zero compared to the 1200 Mio.t in 2008.

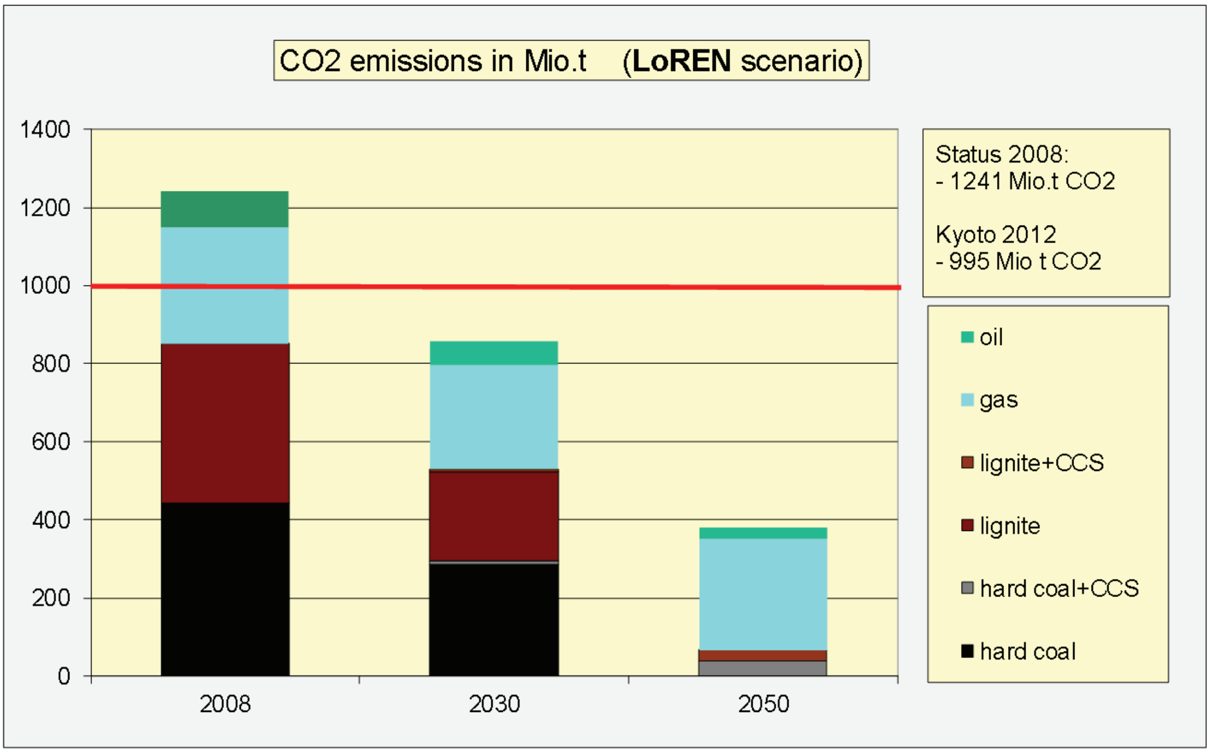


Figure 86: CO2 emissions in Mio t in 2050 for EU27+ (LoREN scenario)

The transformation of the power industry in EU27+ in such a dramatic way as described above will cost very high investments for the erection of the necessary new or refurbished power plants. On the basis of the 2011-prices this transformation will sum up over the next 4 decades from 2010 to 2050 to nearly 3.900 bill € investment costs (figure 87). The main share of this enormous sum is resulting from the investments in photovoltaic and wind power stations, 1150 resp. 900 bill.€. About 350 bill. € must be invested in the backup gas power plants for the volatile renewable generation. The high costs for the renewable generation with wind and sun results mainly from the low full power operating hours compared to that of the fossil power plants. (Remark: This study does not estimate the total cost for the generation, i.e. including the fuel and operation costs. It is impossible to seriously estimate the fuel costs of coal, oil, gas and uranium for such a long period, even not in relation to other standard cost of living. The only way is to estimate these costs on a today-price basis).

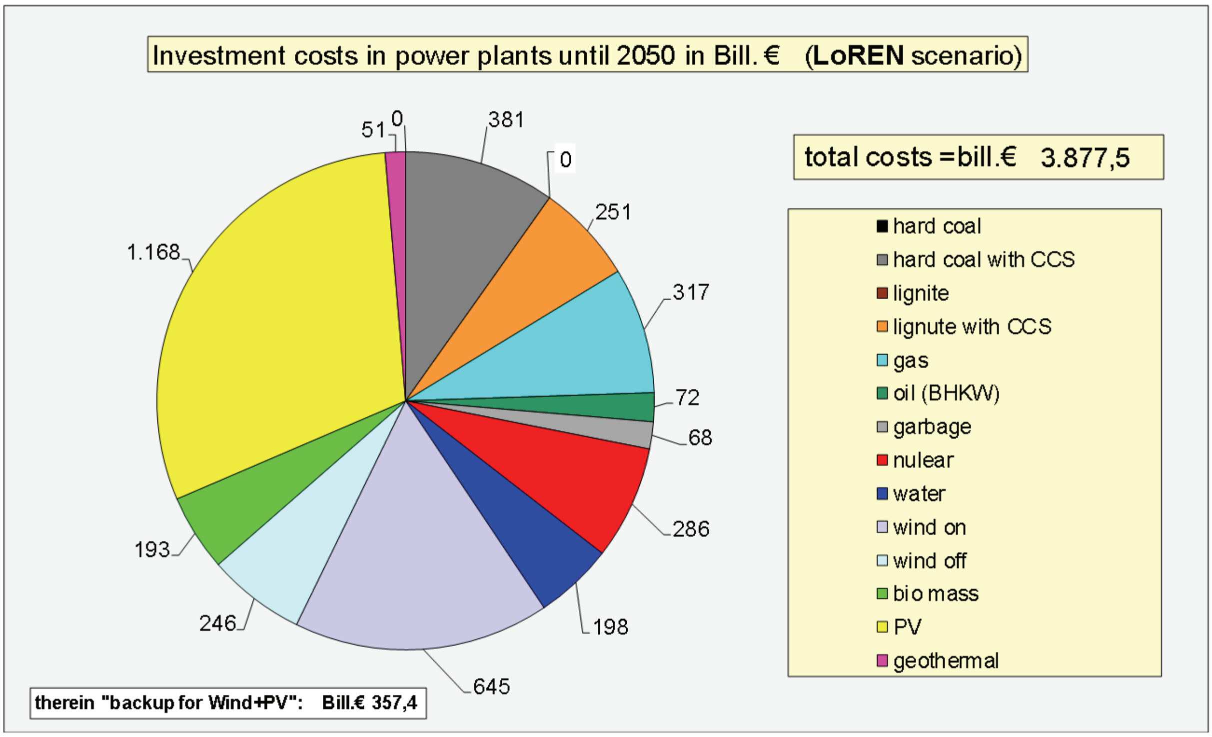


Figure 87: Investment costs in power plant in bill. € until 2050 (LoREN scenario)

11.4 The HiREN Scenario

As for the LoREN scenario the consumption estimation in chapter 5 is also the base for the necessary electricity generation in the HiREN scenario. In the progressive approach the total demand in 2050 is calculated to 4950 TWh.

The HiREN scenario is described by 4 objectives: reduction of the GHG by 80% until 2050 compared to 1990, expansion of the renewables as primary energy resource to 80% of the total electricity production and the phase-out of nuclear and coal power plants. This strategy will result in the following generation mix: gas, oil and other fossil contribute 18% and all the renewables 82%. Within the renewables water has a share of 14%, wind 29%, biomass 12%, PV 19% and geothermal 8% (see figure 88).

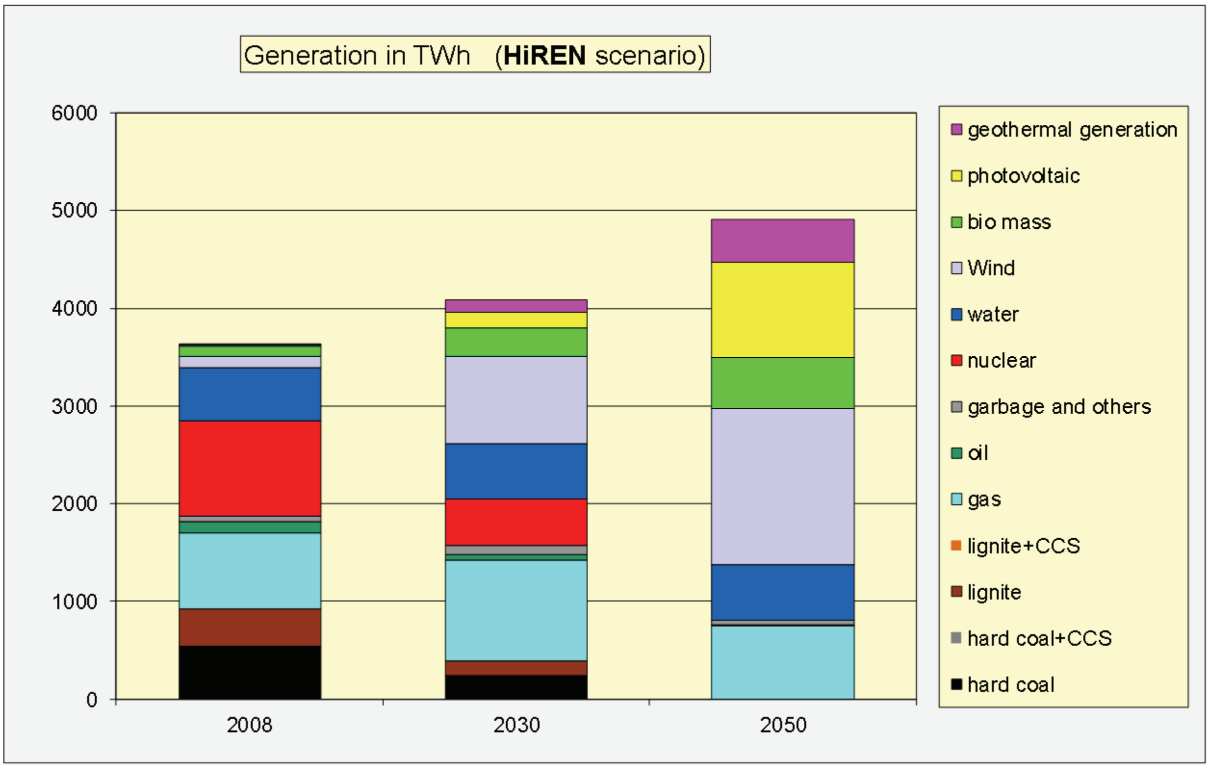


Figure 88: Generation in TWh in 2050 for EU27+ (HiREN scenario)

Although wind will deliver the largest contribution to the electricity generation in 2050 the biggest portion of installed power capacities would come with 1200 GW or 37% from PV power stations (figure 89). The second largest capacity will be gas with 27 %, followed by wind with 22% and water with 7%. The rest of the installed power capacities are fuelled by oil, biomass and geothermal heat.

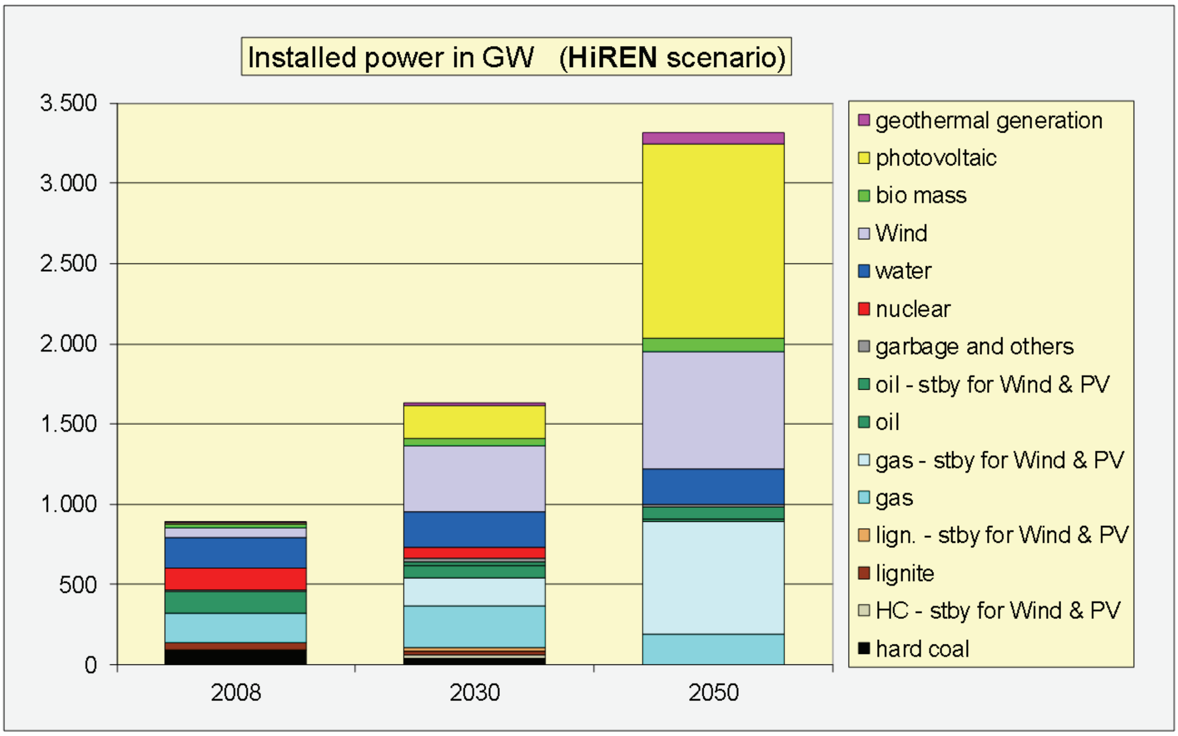


Figure 89: Installed power in GW in 2050 in EU27+ (HiREN scenario)

Since there will be no coal power plants in the HiREN scenario in 2050 the GHG emission will be reduced by more approximately 80% compared to the level of 1990 (figure 90). Only the gas fired power plants will emit CO2 when producing electricity. As in the LoREN scenario even this could be reduced by applying CCS technology to the gas and oil power stations.

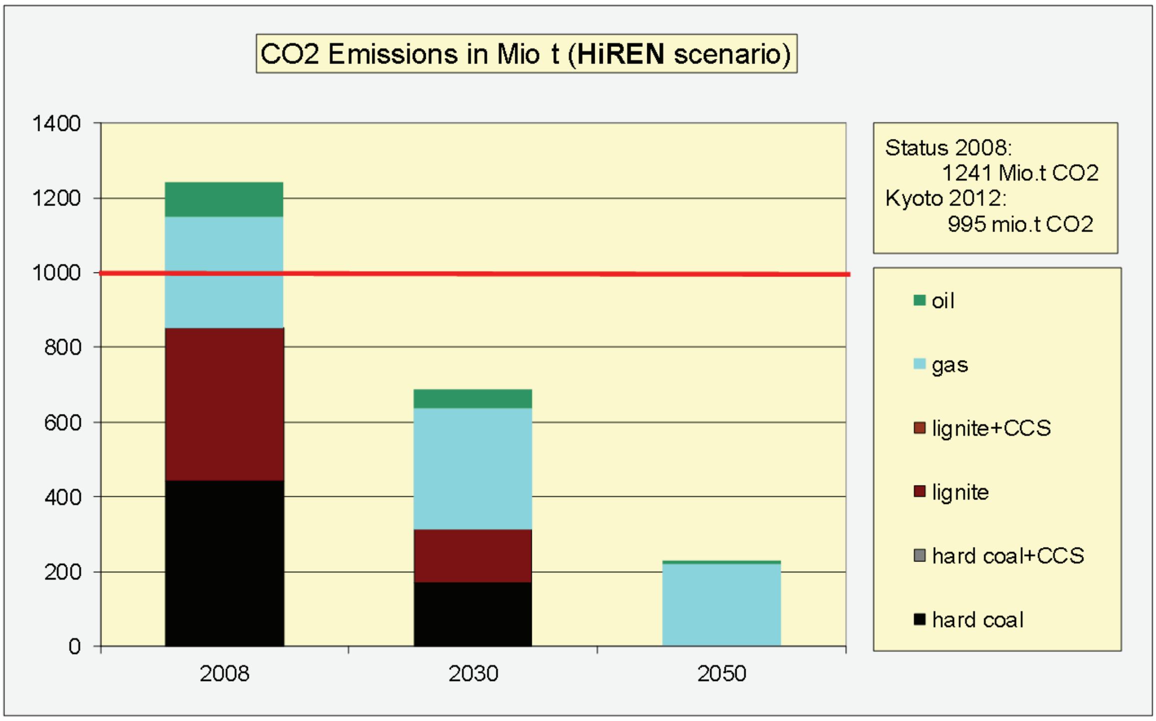


Figure 90: CO2 emissions in Mio t in 2050 for EU27+ (HiREN scenario)

Because of the higher share of renewable resources in the generation mix the investment costs of the HiREN scenario are much higher than those of the LoREN scenario. In the period up to 2050 the investment costs will climb to 5.800 bill. €, whereof the costs for the PV power stations will have a share of nearly 60% or 3.300 bill. €. The necessary investment in wind turbines would sum up to 1.150 bill. € and gas power plants to 550 bill. € (figure 91).

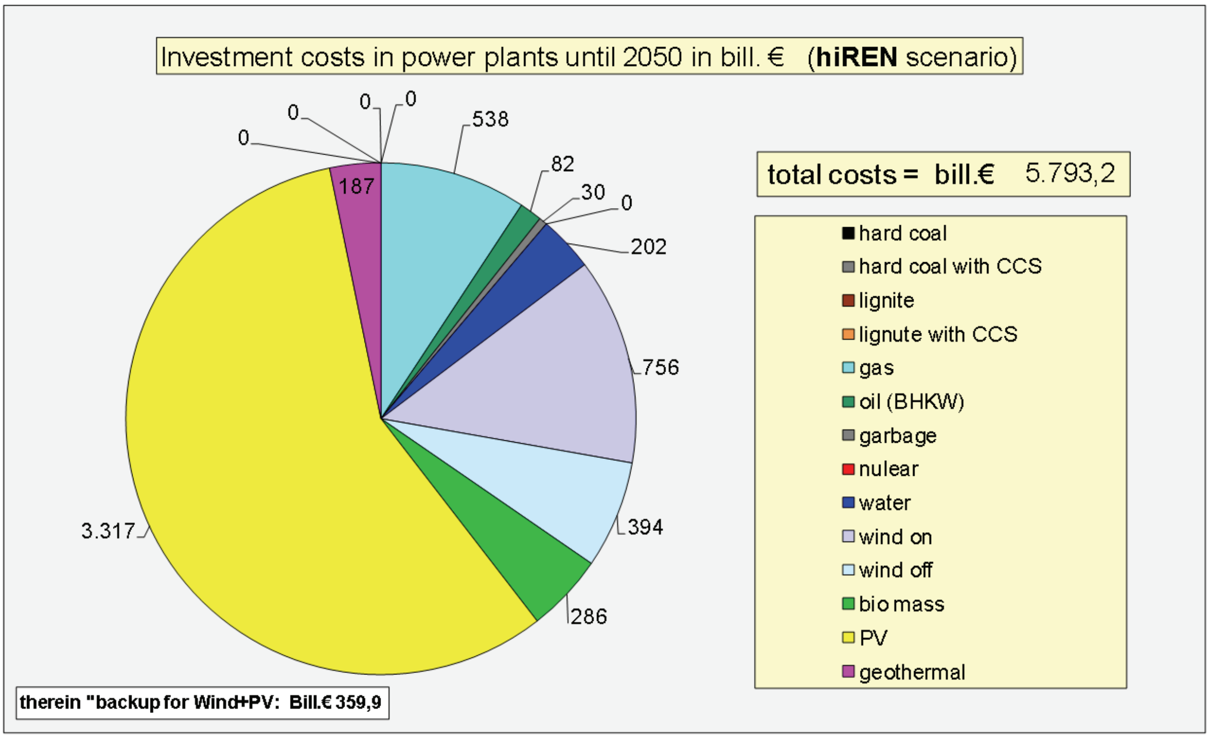


Figure 91: Investment costs in power plant in bill.€ until 2050 (progressive scenario)

11.5 Comparison of the scenarios

Due to the power consumption growth the generation will increase from 2008 to 2050 by 40%. This growth will be mainly generated in all scenarios by renewable resources. In HiREN the renewable generation jumps up to 80%, while in LoREN its share is about 50%. In the TREND scenario the renewables count only for 40% of the generated TWh´s. TREND has nearly the same fossil and nuclear generation as today while in LoREN the nuclear generation is cut by half mainly due to the German exit. Since in HiREN no nuclear and coal power plants will be used any more the fossil share in generation (gas) is dropping to 20%.

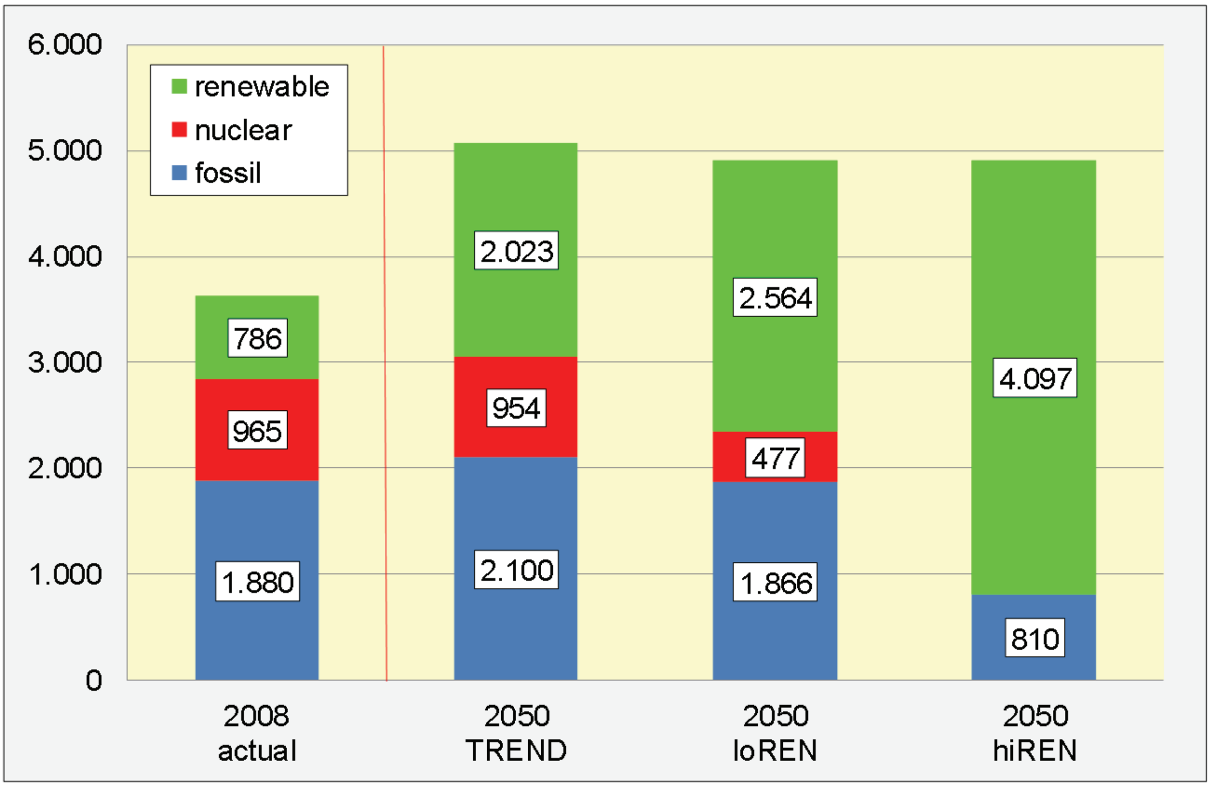


Figure 92: Comparison of generation mix

Totally different is the picture for the installed power capacities. Due to the high share of renewable resources for the generation of electricity and the very low full load hours of PV panels or wind turbines the installed power capacities will rise to extreme high values. In HiREN the installed capacity of renewable power stations increases from 283 GW in 2008 to 2300 GW in 2050 in order to generated the needed TWh´s. The installed capacity of renewables in HiREN is 100% higher than in the TREND and still 60% more than in the LoREN scenario. The nuclear power capacity was in 2008 136 GW. It will stay on that level in TREND and will be only half of that in LoREN. In the HiREN scenario no nuclear power plants are in use. The fossil capacities in daily operations will stay on the today level of about 450 GW in the TREND and LoREN scenarios and will go down to 260 GW in HiREN in 2050.

The peak load in 2008 was about 500 GW. So the installed power capacity of 600 GW fossil or nuclear power plants could easily cope with the situation. With the increasing capacity of wind and PV power stations in the future there must be adequate fossil or nuclear power capacity to handle the peak load situation in case there is no wind and sunshine.

In all three scenarios there must be enough reserve power installed (light blue capacity in figure 92) to guarantee supply in the peak load situation. The peak load in 2050 will be about 700 GW. The needed installed fossil and/or nuclear capacity must therefore be in the range of 850-950 GW, which is the case in all three scenarios. Table 4 gives an overview on the power capacity situation:

Table 4: Peak load and installed power

	Scenario	peak load (GW)	installed power (GW)
2008	acual	490	880
2050	TREND	680	1800
	loREN	680	2200
	hiREN	680	3400 (!)

In certain time periods where the sun is intensively shining and the wind is heavily blowing the generated TWh´s might not be used because of the lack of demand. In those cases the photovoltaic and wind power stations must be switched off. As long as there are no useful and big size power storages and enough demand side power shift capacity where the generated energy can be stored or used the switching off is the only way to handle the situation.

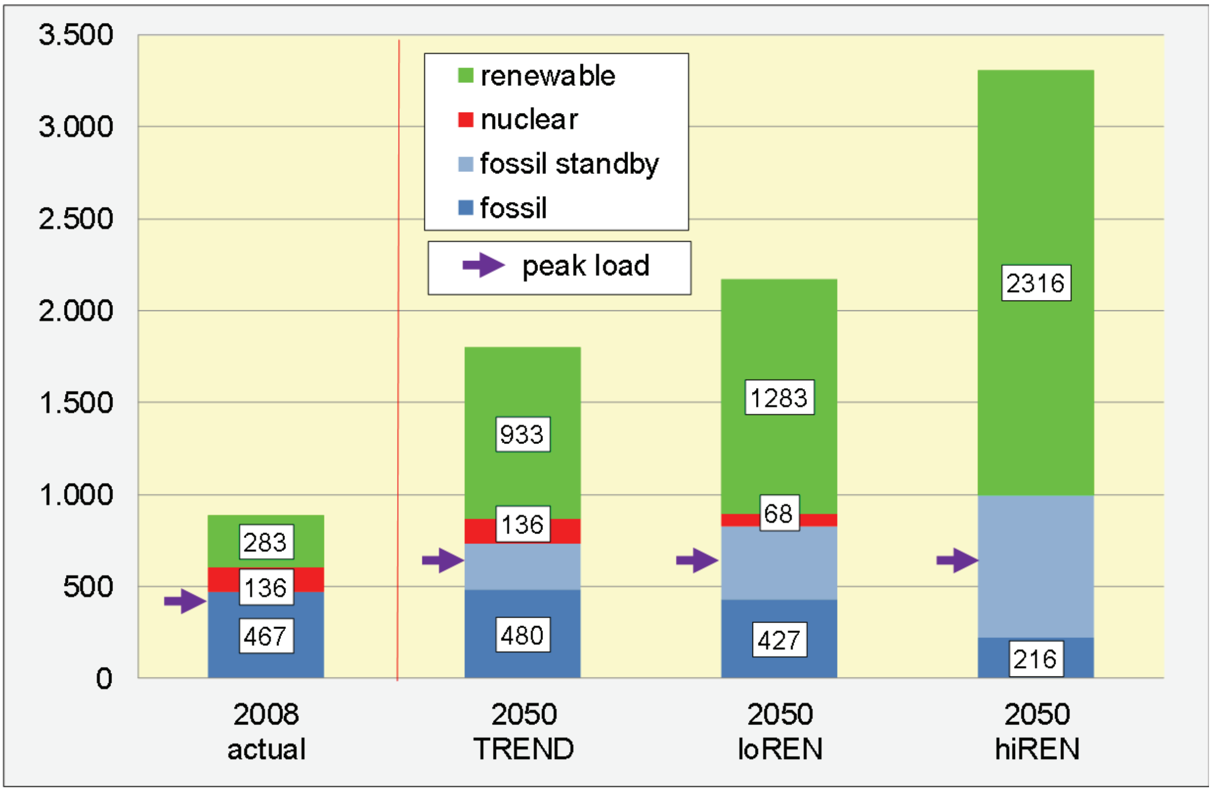


Figure 93: Comparison of the installed power mix

The share of the renewable power capacities influenced heavily the investment costs for the time period 2010 to 2050. Figure 93 reflects this situation. While in TREND the total investment costs sum up to 3.200 bill.€, the investment costs for the HiREN scenario are nearly twice as much. The lion´s share with 5.100 bill.€ (5,1 x 10^{+12} €!) is for the erection of the renewable power capacities. It is more than three times as in the TREND scenario and twice as in the LoREN scenario. The fossil and the nuclear power plants do play only a minor role with regard to the investment costs, especially in the HiREN scenario.

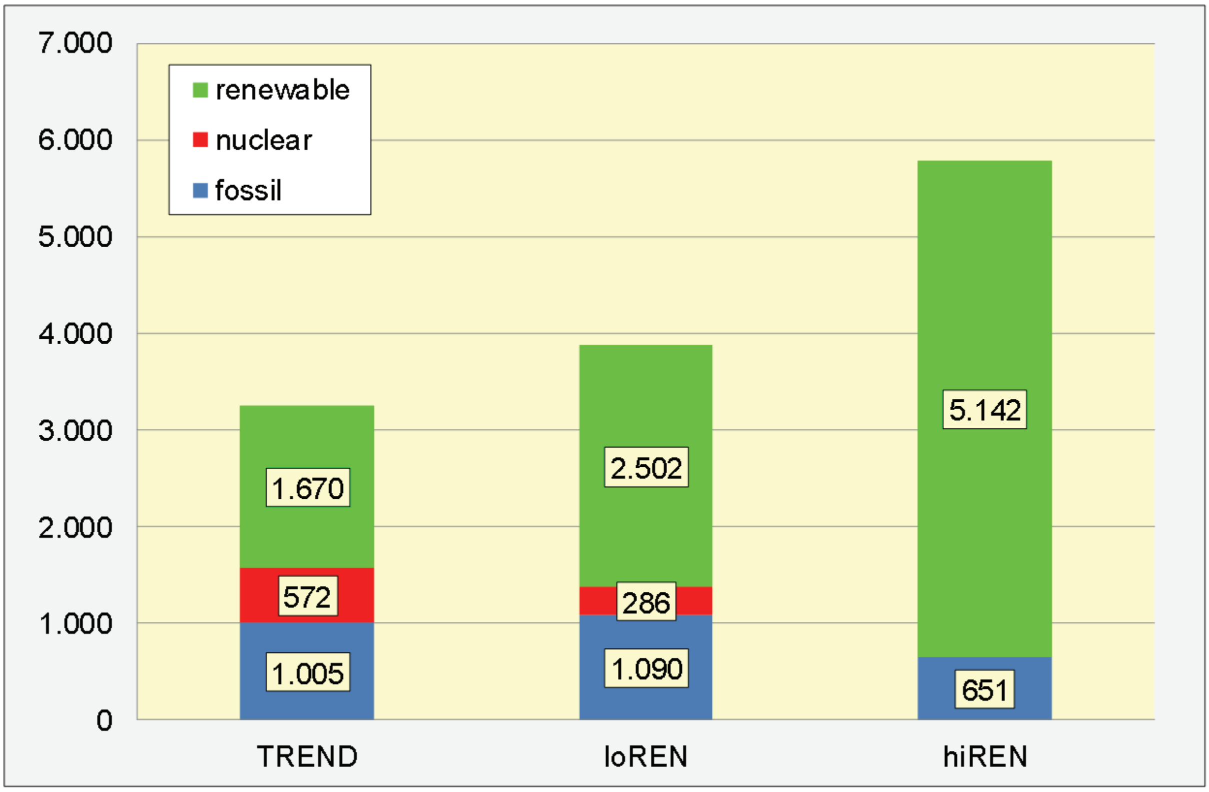


Figure 94: Comparison of investment costs in bill.€ for 2010-2050

The CO2 reduction from 2008 to 2050 is shown in figure 94 for all three scenarios.

While in the HiREN scenario the CO2 emissions are reduced by nearly 80% compared to 1990 the reduction in the two other scenarios reaches after all two thirds of the origin emissions.. In the HiREN scenario this reduction is achieved mainly by the high share of the renewables in the generation mix and since no fossils are used besides gas. The TREND scenario accomplishes 66% CO2 reduction by using nuclear power and CCS technology filtering the CO2 out of the combustion gas. The same is true for the LoREN scenario. Here the lower share of nuclear generation is compensated by a higher share of renewables.

All three scenarios achieve very good results with regard to the GHG goal of the European Union. The question is the acceptance of the used technologies by the public.

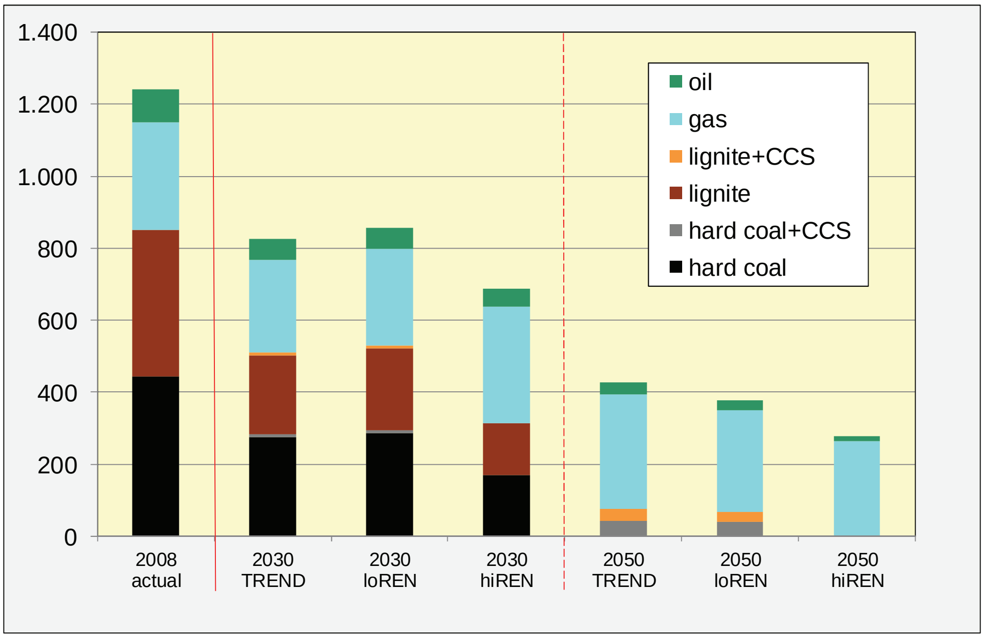


Figure 95: Estimation of the CO2 emissions in mill.t in 2030 and 2050

12. Outlook for a future power supply system

The power supply system of the future will be dependent on the availability of the type and amount of the primary energy source. Since it is common understanding that fossil sources like gas and oil will run short in this century we have to look to other energy sources. Coal will still be an option but we have to solve the CO2 challenge. The CO2-capture-and-store (CCS) technology is an option but there is already opposition in the public because of the unclear long-term storage question.

The same is true with the nuclear energy. The nuclear option in form of the breeder reactor technology would be a long term solution for the power supply. But as long as we do not have a true secure technology at hand and until there is no solution ready for the nuclear waste problem people would not accept it. A long term solution might be the nuclear fusion technology which is still to be proven. Even if it will work it is unclear if the environmental challenges will be solved and accepted by the people. Still the nuclear technologies for fission and fusion should be explored for a future feasible solution.

As consequence of the uncertainty in the fossil and nuclear field the use of renewable energies is more and more considered as a solution for the future: water, wind, bio mass, sun radiation and geothermal heat. Water, bio mass and geothermal heat can be incorporated into the electricity generation quite nicely. But they have restrictions: the available and economical usable water resources are limited as are the bio mass resources. Furthermore the ashes problem is not solved: where to deposit the huge amount of ashes out of the bio mass combustion process.The use of the geothermal heat is a very interesting option but the technology is not yet economically proven and only locational available. The petro thermal system is not yet explored for the geothermal use. So at present wind and sun radiation are the options at hand.

Both are available basically everywhere. Their main disadvantage is their volatile and uncertain character. To counterbalance this we have to use huge storages of water or gas (H2, CH4 or similar) and we have to provide fast reacting fossil power plants to jump in when needed.

Hydro and gas storages are at present not available with the necessary storage capacities. Long term H2 and CH4 can be options. Water pump storages can have only supplementary character. Therefore today we have to use fossil power station, mainly gas power plants, to overcome the unavailability of wind and sun at certain time periods. This is possible, but it means high investment and operation costs for the needed standby power plants. Typically the standby cost are 30% of the full power costs.

The specific character of wind and sun leads often to smaller power stations. So we have to deal much more with distributed power generation instead of centralized big generator plants up to now. Nevertheless we will have also partly concentrated wind and solar thermal generators in form of big off shore wind parks and big solar fields. This has high potential and this should be explored more deeply.

For the backup support we still will have huge fossil power stations. So the future structure of the power generation will look like the principal layout in figure 96. It will be a combination of big and small generators, the small ones for the more local supply and the big station for the system backup and as a bridge for time periods with no wind and useful sun radiation.

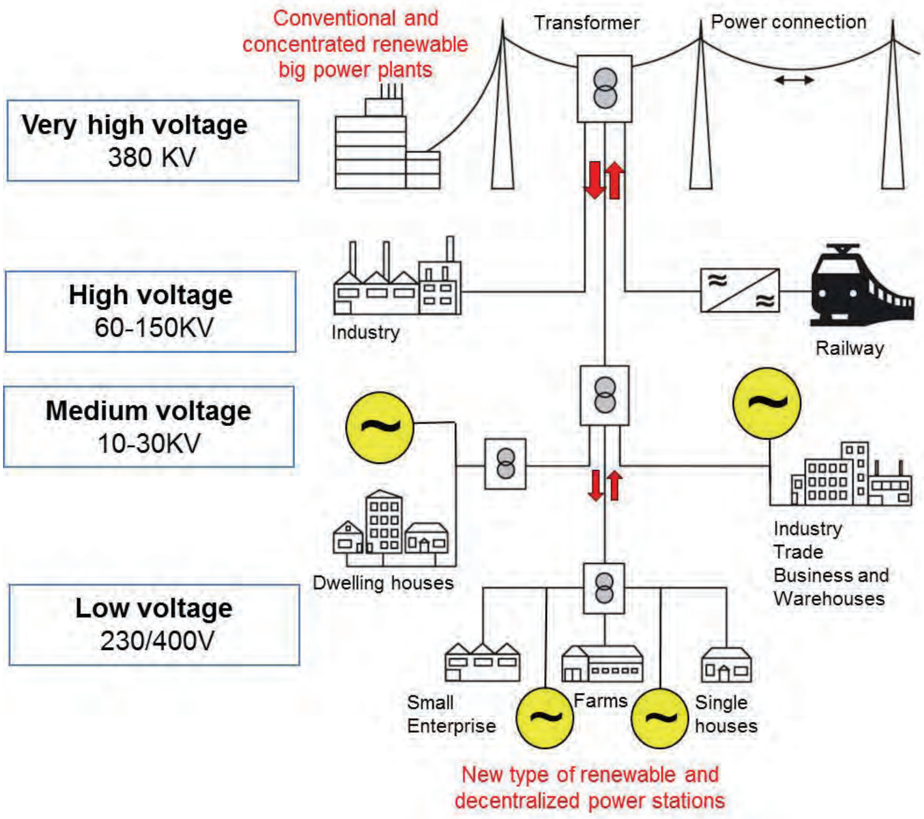


Figure 96: New structure of the power generation scheme

This new scheme of power generation will require a new power network scheme. For the local power supply so-called micro networks will bind together the different types and huge numbers of generators and will organise the local balance of the power system. If a micro network cannot achieve the balance then it will get support from the neighbour micro grid or the strong backup system (constant frequency!).

The backup network might be an AC or DC network. This is a matter of technical and economical optimization, a matter of loss avoidance and a matter of smooth transition from today´s installation to the future system.

This new scheme requires very sophisticated control systems which must optimize the local and the global control jointly. A huge task! The cooperation of a big number of local networks with active customers and small storages and a strong backbone network with powerful generators is called in modern terms a Smart Grid.

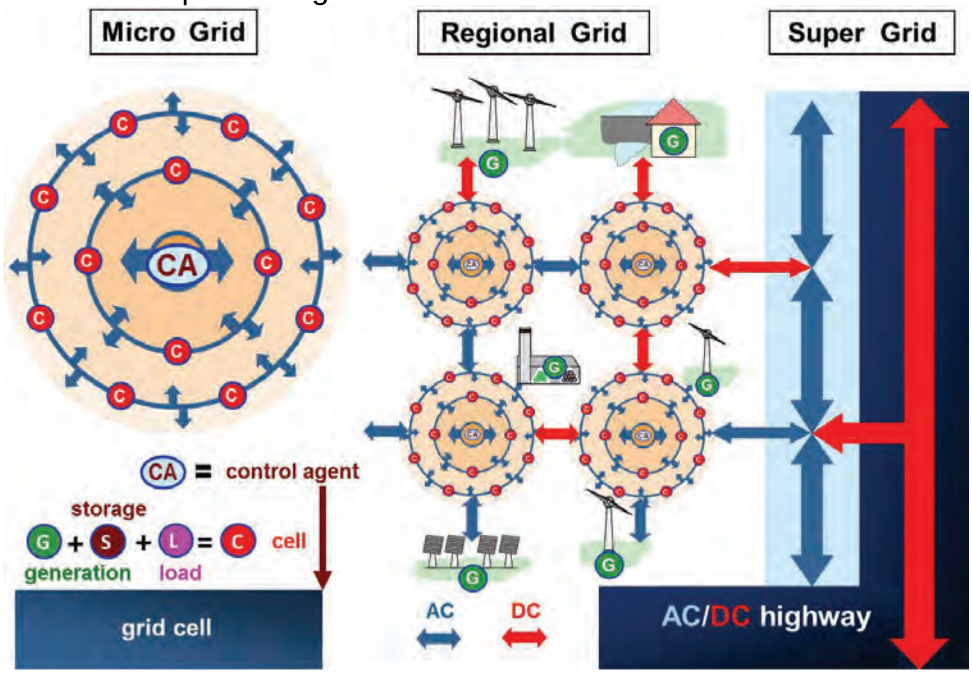


Figure 97: Structure of a future power supply system (Origin: Siemens)

Figure 97 describes exemplarily this new power supply system composed of local and global networks, local and global power generators and intelligent control systems.

The power supply system infrastructure will be linked in the future to other infrastructures. Beyond the storage capability, the production and utilization of hydrogen or synthetic hydrocarbons offer additional wide-ranging opportunities (figure 98). Coupling of the electricity and chemistry opens multiple synergies between infrastructures for power-, heat- and mobility-sectors. It unlocks efficiency gains and savings of fossil energy and consequently of $CO2$ emissions.

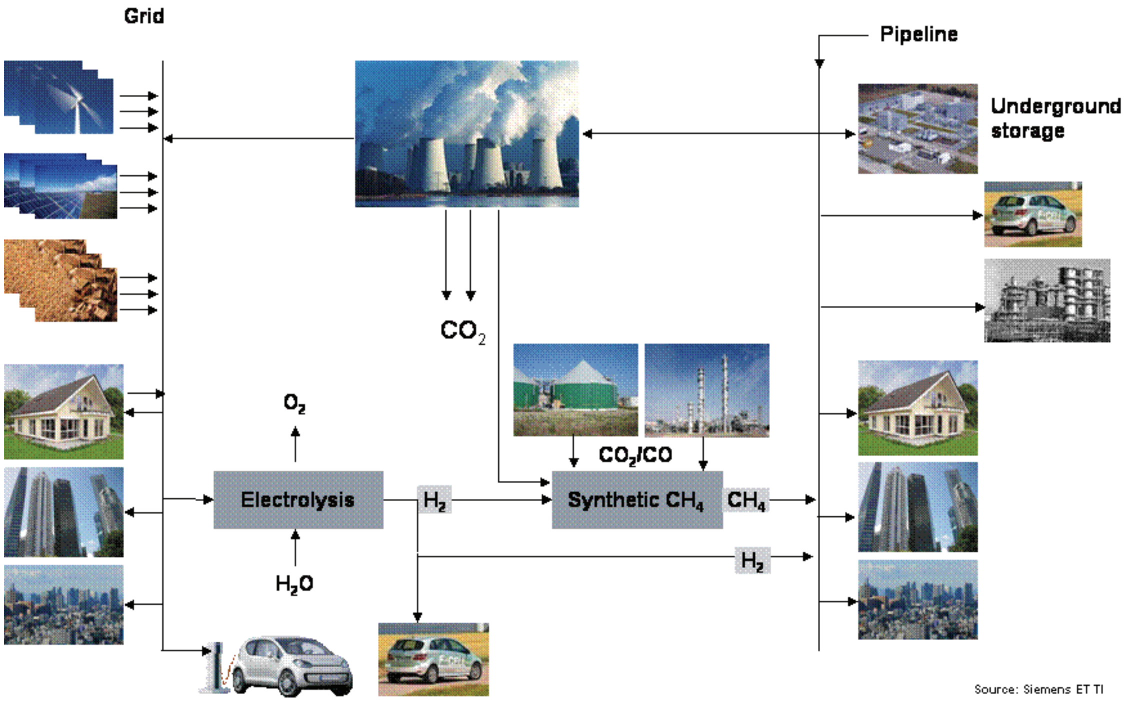


Figure 98: Synergies between the infrastructures for electricity, heat and mobility

Although several technical basics of this new and complex system are already well understood, as well as selected components already commercially available, further actions are still needed. They include an accelerated development of few key system components like storage technologies, or electric cars and their infrastructure. The

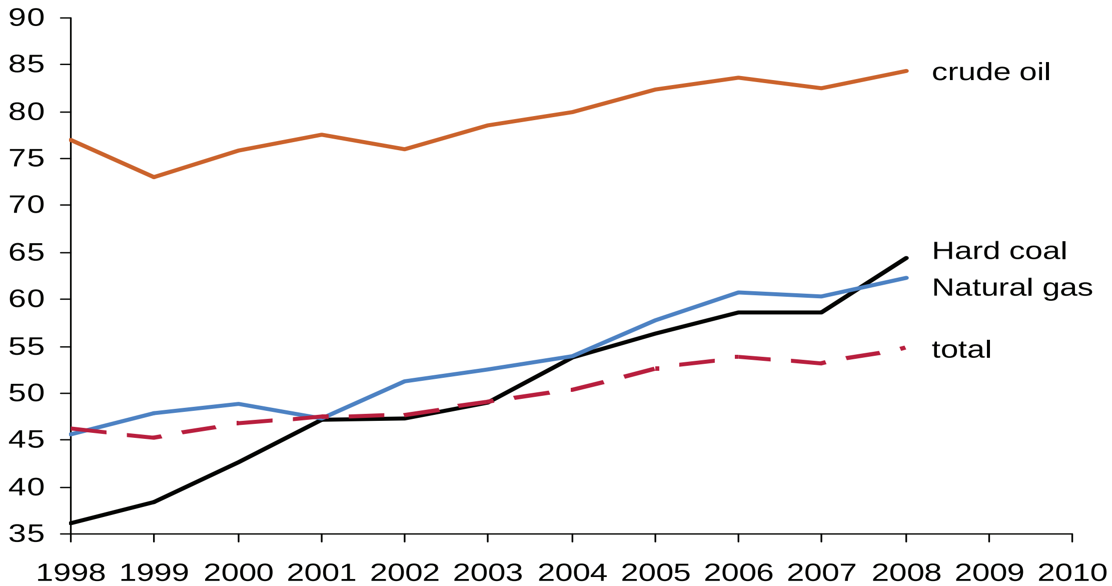


Figure 99: EU27 import-dependency of fossil fuels

implementation of the another key system enabler, which is a reliable and secure bidirectional information and communication technology, which will be connecting the multiple system-components between and within infrastructures in an intelligent way, is urgently needed as well. Beyond the technology development, improvements of system economics have to be realized. They will be depending on the one side on the future cost degression for new technologies, on the other side on the availability and prices of fossil fuels, like crude oil and natural gas. Because they are mainly being imported to Europe the European energy policy is requested to provide a right frame work to decrease the historically rising energy import dependency (figure 99) and improve in this way the security of the future European energy supply.

In this manner, the integration of wind and solar power and opening the implementation of electricity to produce hydrogen and synthesize gaseous or liquid hydrocarbon will open the door to a new European “electricity age”. It offers substantial opportunities to establish a full renewable energy supply, increase energy efficiency mainly by the change from mechanical to electrical drives and to improve the European supply security by decreasing the import dependency of fossil energy carriers.

13. Conclusions and recommendations

13.1 Conclusion from the scenarios

The European commission has laid down three main targets in their roadmap 2050 document:

- decarbonisation, i.e. 80-95% reduction of the GHG Emissions compared to 1990
- Security of energy supply, i.e. reduction of import dependency
- Security of competitiveness, i.e. affordable energy prices

The decarbonisation target can be reached totally by the HiREN scenario, the two others scenarios come with a CO2 reduction by 66% close to the -80% goal. The HiREN scenario reduces the import of oil, gas and Uranium raw resources and thereby the import dependability drastically. But this is extreme costly (6.000.000.000.000 € investment costs in the next 40 years)

So the HiREN scenario might influence the EU´s competitiveness to a certain degree. If the investment costs are divided by the kWh´s produced in the period 2008-2050 the kWh **costs** are increased by 3 ct/kWh (**cost is not price!**). This is substantial compared to the current generation costs from fossil energies of 3-5 ct/kWh, nearly a doubling. (It is noted that in this cost analysis no costs for fuels, operations, further infrastructure investments and taxes are included. It's absolutely impossible to estimate those costs for such period of 40 years).

In both, the TREND and the LoREN scenarios, the import dependability from fossil primary energy resources still stays high. The EU would depend to a large extend from countries like Russia, China, Middle East and North Africa. Furthermore both scenarios run the risk of the acceptance of the nuclear and CCS technology by the public. In case these technology are not accepted by the citizens their further existence and application is obsolete.

Table 5: Summarizes the result of the scenarios with regard to the EU 2050 main goals

	TREND	LoREN	HiREN
Decarbonisation	+	+	++
Security of supply	--	-	++
competitiveness	0	0	--

The HiREN is the best choice with regard to environmental aspects and the supply security. The TREND and LoREN scenarios are less costly and therefore contribute to the competitiveness of the EU significantly.

A precondition to establish a power supply system with an extreme high share of renewable generation is to enforce the transportation and distribution grid. The transportation grid must be extended to a high capacity backbone network in order to deal with the fluctuation of renewables such as wind power and sun radiation. Parts of such a backbone network can include point-to-point DC links to prepare for big power transfer over long distances. For example big power transfers are needed in Germany to transfer offshore generated power by big wind parks to the industry centres in the southern and western regions of Germany over some 500 km. Later these point-to-point links can be incorporated more smoothly into the meshed transport network if DC power switches are available. With these DC switches high capacity DC networks can to establish.

Another prerequisite is to either provide extreme large seasonal storage capacities or fast reacting gas turbine power stations to jump into power production when the wind is not blowing and the sun not shining. This situation can occur in winter time over some days or even some weeks. Since we do not have today those big storages to fill the gap the only choice is to use conventional gas turbine power plants. **A 100% backup power capacity must be provided for the renewable generators.**

In case we would have huge gas storages (CH_4 or H_2) - big enough to store the electric energy equivalent of some weeks of the electricity demand – the total system could be fed only by renewable power. But these renewable capacities must be big enough to supply the actual power demand and to fill the storages with synthetically produced gas; this capacity must be a multiple of the actual load. A futuristic vision!

13.2 Recommendations and need for action

The transition from the today power supply scheme to a future system as described above will be a matter of decades. Therefore it is important to have a clear and sound strategy. The implementation of the strategy might be different in the various member states of the EU27+, but it should follow the same basic concept and rules. All European countries have the same challenge with the fossil and nuclear energies and with a few exceptions the same problem of primary energy import dependency. For the European Commission and all member states the following basic recommendations will apply:

- massive increase of power efficiency of devices, products, systems, installations and plants
- development and funding of programs to reduce peak power and in general energy
- funding of research and development in all fields of power generation (fossil, nuclear and renewable), transmission and storage technologies

- increasing use of renewable energies for electricity and also heat production.
- step by step reduction of the import dependency of EU27+ on fossil energies like gas, oil and coal by a continuous transition to renewable energies
- funding of technologies which increase power efficiency in power stations
- stimulation of investments in modernized or new power stations and power networks
- stimulation of investments in low loss long-distance transmission schemes (backbone network: HVDC, UHVAC) and intelligent energy-active distribution network technologies
- stimulation of investments in smart control, protection and self-healing functions

All programs of the EU Commission and the member states must have a long term character and **should not be driven by short term actions** which change from year to year dependent of the political climate. Basic for all actions must be a **sound and farsighted system** of the electric supply system taking into account all dependabilities and requirements of a sustainable and stable system. Singular and ideology oriented interests will not lead to functional and optimized total system. The design of a future supply system has also to take into consideration environmental requirements. Even using renewable energy generators does not mean always environmental compatible solutions. **We should not seek for fast and populist, but firm and sound solutions**. The above described HiREN scenario (reduction of the GHG by 80% until 2050 compared to 1990, expansion of the renewables as primary energy resource to 80% of the total electricity production and the phase-out of nuclear and coal power plants) is the most attractive and ambitious out of the three investigated scenarios. But it is very expensive. Will the society accept these costs?

Coordination of actions and development in the power and transmission sector between the member states is basic to achieve the common goal.

For long term investments the industry **needs stable conditions and perspectives**. Otherwise the European goals with regard to a future, sustainable power system will not be reached.

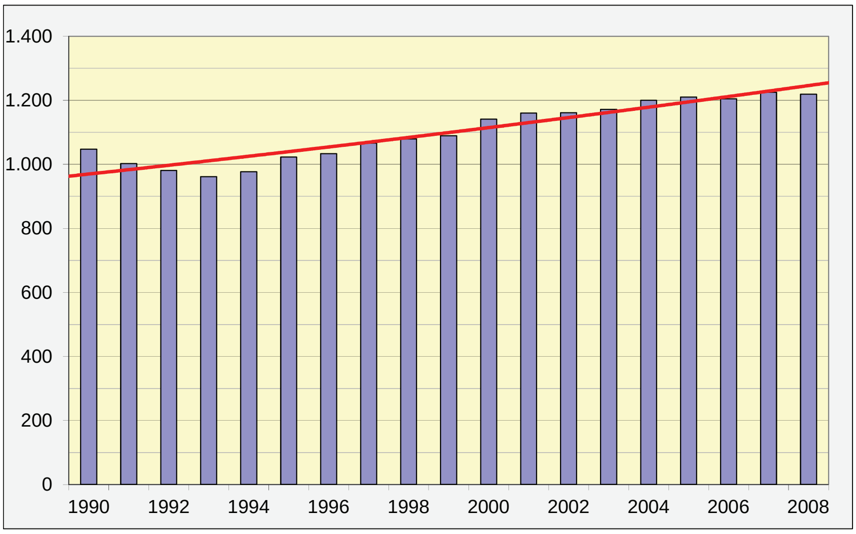
14. Appendix

14.1 Appendix: Daily demand for warm water

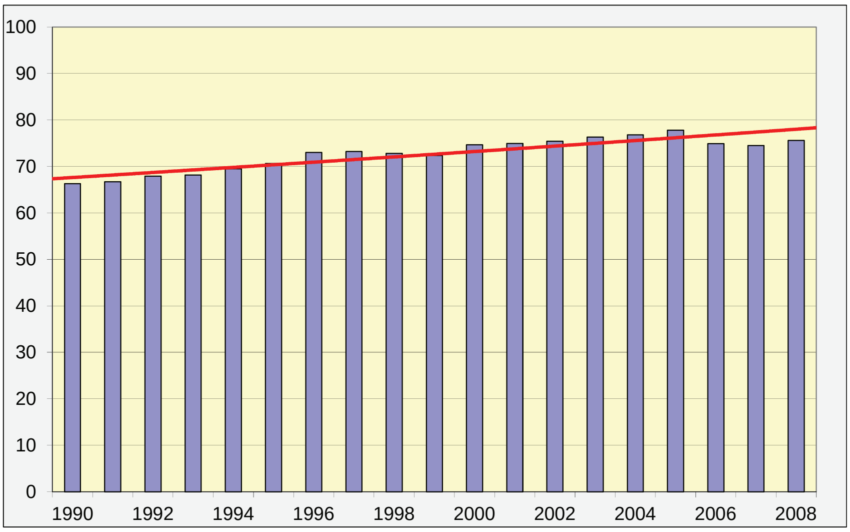
Shower	50 liter	40°C	1.6 kWh/d
Hand washing	5 liter	35°C	0.2 kWh/d
Dish washing	30 liter	38°C	1.3 kWh/d
Total thermal energy			3.1 kWh/d
Total annual energy 320 days			992 kWh/a
Solar harvesting 85%			850 kWe/a (rounded 1000 kWh/a)

14.2 Appendix: Power consumption development from 1990 – 2008 in TWh

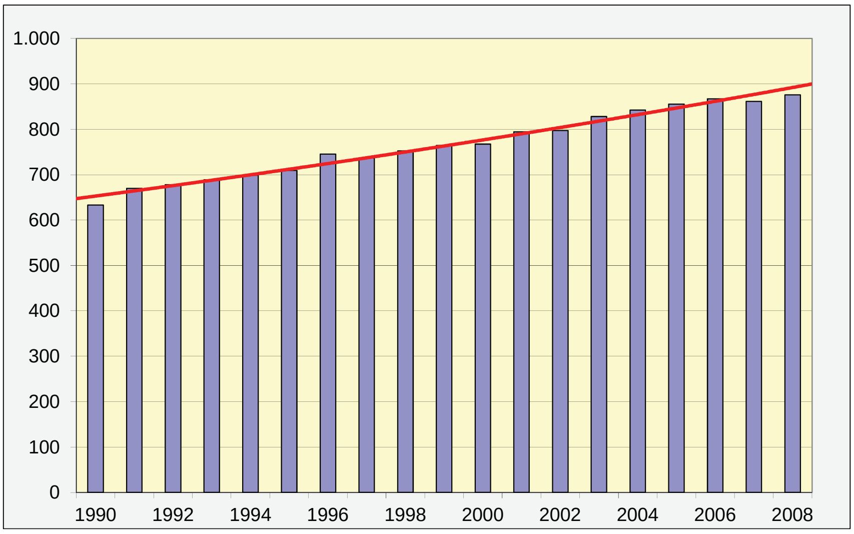
- Industry sector



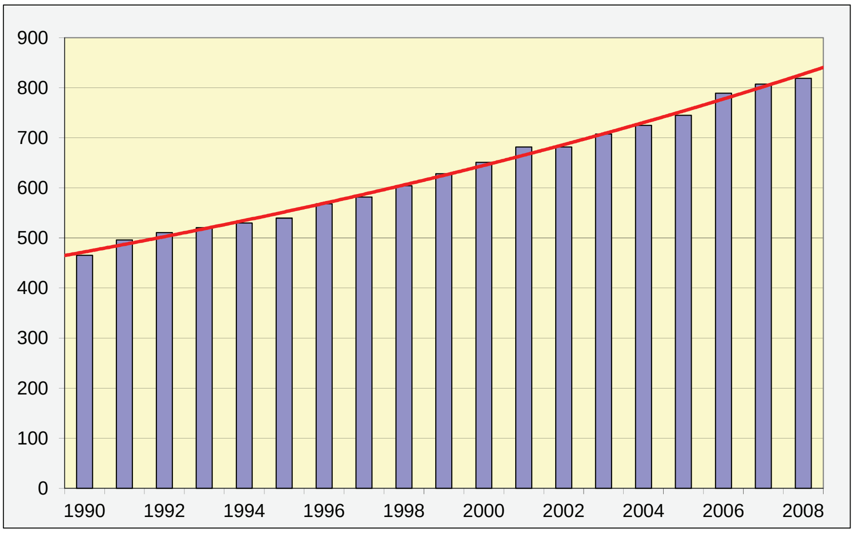
- Transportation sector



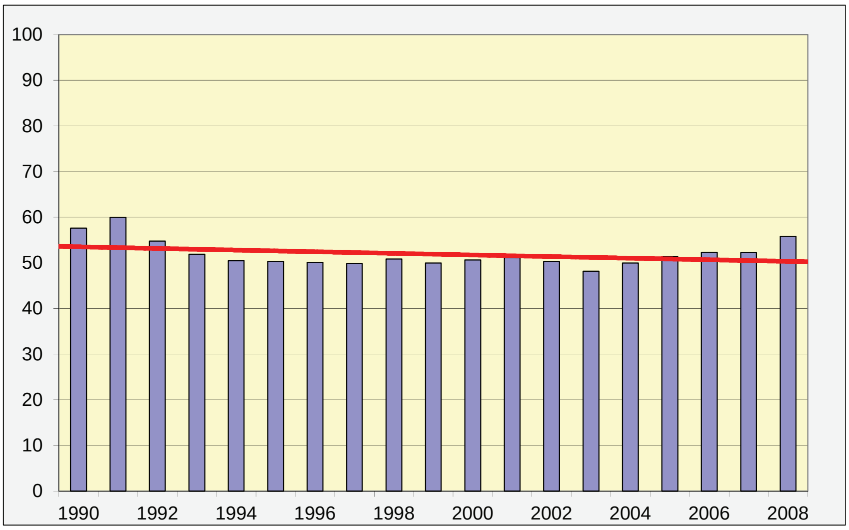
- Residential sector



- Services sector



- Agriculture sector



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