Long-term scenarios and strategies for the deployment of renewable energies in Germany in view of European and global developments

Summary of the final report

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1 Initial situation

The German Federal government's 'Energy Concept' [*Energiekonzept 2010*] of 28 September 2010 and the subsequent energy laws of summer 2011 presented a long-term political timetable for climate protection and the transformation of the energy supply in Germany [the "*Energiewende*"]. It calls for emissions of greenhouse gases in Germany to be reduced by 80% to 95% from the 1990 level by the year 2050. For energy-related CO_2 emissions alone, this target requires a reduction of at least 85%, aiming in the final result at a power supply that is almost emission-free. A transformation of the power supply to renewable sources of energy, accompanied by a substantial increase in energy efficiency, is the appropriate strategy for this. The challenges presented by this transformation of the power system are considerable, and their full extent has not yet been grasped. This study presents results of systems-analysis examinations of the transformation of electricity, heat, and fuel generation that were developed as part of a three-year research project for the Federal Ministry of the Environment (final report [Nitsch et al. 2012]). The work is based on projects carried out in previous years by the DLR with varying project partners for the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU) and the Federal Environment Agency (UBA). In essence, self-consistent energy scenarios for long-term expansion of renewables and for the remaining supply of energy, and the structural and economic effects to be derived from these, were developed. In addition, the project partners, the DLR in Stuttgart and the Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES) in Kassel, performed simulations of the future electricity supply as it develops over time, some of them with spatial resolution. This enabled the scenarios for electricity generation to be validated with respect to load coverage, and also the role of load-equalization options, such as flexibilization of conventional power stations, extension of the grid, load management, and the use of electricity storage systems, to be studied.

2 The scenarios and their principal particulars

The long-term scenarios presented in this study are – as in all its predecessors – target-oriented scenarios. Therefore, they must not be interpreted as a "forecast" of the future development of the energy system. The quantified targets for transforming the energy system in Germany, approved and confirmed by the package of energy laws in summer 2011, set the framework for their design. In compliance with the technical and structural options for the transformation of the energy system, and taking into account economic, political and social realities, interests, and the resulting barriers and incentives, several consistent development paths are presented that meet these targets. In comparison with the current situation, recommendations are derived for necessary extensions and modifications of the existing energy policy instruments.

The scenarios are oriented to the overall goal of the Energy Concept, an eighty-percent reduction in greenhouse-gas emissions by 2050, and also meet the subsidiary goals with respect to expansion of renewables and increases in efficiency for the most part. This also includes the target of a 25% reduction in electricity consumption by 2050 (relative to its consumption as final energy in 2008). This consumption of electricity includes electromobility and other new consumers such as heat pumps. However, electricity demand for generating the synthetic energy carriers hydrogen or methane is not included in this efficiency target. The scenarios show clearly the structural changes associated with **meeting the political goals**. Among other things, the scenarios illustrate **different paths of development in the transportation sector**, and their implications for an energy system with high proportions of renewable sources. For this purpose, the following variants of the scenarios are examined:

- **Scenario 2011 A** is the middle variant of the three “main scenarios” with respect to energy demand and the pathway of expansion of renewables. Fully electric vehicles and plug-in-hybrid vehicles reach a share of the mileage of passenger cars of 50% in 2050. Other motor-vehicle transportation is provided by means of biofuels, vehicles using hydrogen, and remaining conventional vehicles that are more efficient than today. Hydrogen is also applied as a chemical storage medium for electricity from renewables and used in cogeneration for provision of heat and electricity, as well, and for short periods also reconversion into electricity. The national abandonment of nuclear power, in accordance with the Bundestag decision of 30 June 2011 (13th Amendment of the Atomic Energy Act), is taken into account.
- **Scenario 2011 B** is based on the same assumptions about consumption structure and final energy consumption in the sectors of industry, commercial and institutional use, and private households as Scenario 2011 A. But it varies from Scenario A in that hydrogen produced by renewables is converted to synthetic methane by methanation. The possibility of direct injection into the natural-gas grid makes the storage and transportation of CH_4 from renewable sources of energy possible without any additional infrastructure. Methane is used in the transport sector, through an increasing share of gas-powered vehicles, for cogeneration in CHP facilities, and in power plants for reconversion into electricity.
- **Scenario 2011 C** represents, in contrast to Scenario 2011 A, a complete coverage of passenger-car mileage in 2050 by fully electric vehicles as well as plug-in-hybrid vehicles (approx. 80% electric propulsion), i.e. without the use of hydrogen or methane in transportation. In the other final-consumption sectors, the Scenario 2011 C is identical to Scenarios A and B. Hydrogen is only required for long-term storage, and is used to a limited extent for cogeneration and short-term load coverage (reconversion into electricity).

These three “main scenarios” are supplemented by two further scenarios, which illustrate specific points more closely. In **Scenario 2011 A′**, the goal of a 25% electricity reduction is considered as relative only to present “conventional” electricity consumers. This results in a reduction of total final energy in the form of electricity (including novel consumers such as electric vehicles and heat pumps) of 15% by 2050. The demand for electricity from the transportation section corresponds to that of Scenario 2011 A. **Scenario 2011 THG95** provides in addition a preview of the expansion of renewables and improvement in efficient necessary to reach the upper limit of the Energy Concept’s target corridor for reduction of greenhouse gases (95%). The possible development route for such a scenario by 2060 requires energy supplied almost entirely from renewable sources in all fields of use. In this scenario, hydrogen (or alternatively methane) from renewables plays a dominant role as electricity stored in chemical form and for a supply of the heat sector and transportation entirely from renewables.

The **principal demographical, structural, and economic particulars**, that, along with the level of economic activity, determine the overall demand for energy, correspond in the main to those data in the 2010 Lead Study, which are matched to the scenarios of the Federal government’s Energy Concept. In these scenarios, the gross domestic product grows in real terms by more than 40% by the year 2050 (from the 2010 level). The population of Germany declines by 10% by 2050, while the parameters that determine energy demand – passenger mileage, and residential and other floor space – continue to increase slightly. Mileage of goods traffic will increase considerably, on the other hand. Therefore, the requirements for increased energy productivity must be very demanding, if the substantial absolute drop in energy consumption desired in the Energy Concept is to be achieved.

The basis for determining the costs of the expansion of renewables and of the overall power supply are the assumptions made in [Nitsch et al. 2011] concerning future cost trends of renewables technologies, and **updated price pathways** for the trends in fossil-fuel energy prices and prices of CO_2 emission allowances. In price path A ("substantial increase"), the average prices at German frontier for crude oil increase between 2010 and 2050 from 10.5 to 24 $€_{2009}$/GJ, for natural gas from 5.8 to 14.9 $€_{2009}$/GJ, and for hard coal from 2.9 to 8.9 $€_{2009}$/GJ. In Price Path B ("modest increase"), the prices are from 25% to 30% lower in the year 2050. In addition, a Price Path C ("very small increase") is considered, which approximately reflects the price assumptions of the scenarios for the Energy Concept. **Figure 1** shows the derived gas and hard-coal prices free at power station for the three price paths. The effectiveness of CO_2-certificate trading is determined by the specified development in the prices of CO_2 allowances. In order to illustrate fair competition between fossil-fuel and renewable energy technologies from the point of view of climate protection, in this study the price of CO_2 allowances rises to 75 $€_{2009}$/t CO_2 by 2050 in Price Path A, and to 57 $€_{2009}$/t CO_2 in Price Path B. An approximate value of 75 $€_{2009}$/t CO_2 is also used to show the effect of "environmentally correct" pricing – taking into account the potential damage from climate change – on the economic viability of strategies of expanding renewable sources and increasing efficiency.

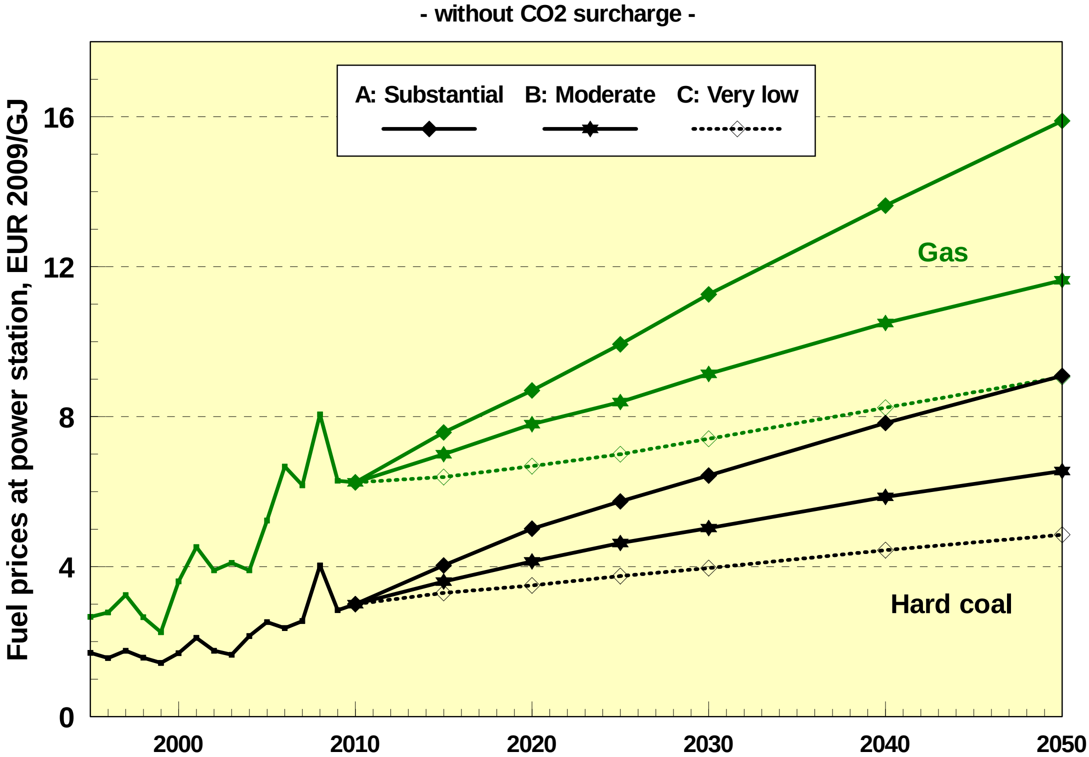


Figure 1: Fuel prices free at power station for the price paths A, B, and C

3 Trends in individual fields of power supply

Electricity consumption (final energy) drops in Scenario 2011 A, in accordance with the goal of the Energy Concept, from 516 TWh (2010) to 393 TWh by the year 2050. For an increase in the GDP from $€_{2000}$ 2274 billion (2008) to $€_{2000}$ 3158 billion (2050), a reduction in the consumption of electricity per unit of economic output (relative to final energy) of 46% must be achieved, which corresponds to an **average annual reduction of 1.5%**. From 2000 to 2010, the specific electricity consumption per unit of GDP dropped by only 0.5% per year on average. Thus the assumed trend in electricity consumption makes great demands on the mobilization of technical and structural potentials for increased efficiency. In Scenario 2011 C, more electric final energy is needed, because of the greater role of electromobility, but due to the lower electricity losses in hydrogen production, the gross electricity consumption is substantially less than in Scenario A.

For the trend in **demand for heat**, it is assumed that the specific final energy consumption for space heating in residential buildings will drop by more than 57%, from 147 kWh/(m^2·yr) in 2008 to 63 kWh/(m^2·yr) in the year 2050. Allowing for an increase in residential floor area from 3460 million m^2 to 3650 million m^2, the final energy consumption for space heating drops to 850 PJ by 2050. To achieve this, it is necessary for almost the entire housing stock to undergo ambitious energy-saving renovation by 2050. Only under this precondition will the targets for the building sector in the Federal government's Energy Concept be achieved: reduction of the heat demand by 20% by 2020, and of the (fossil-fuel) primary energy demand by 80% by 2050. If we consider the total final-energy demand for heat (space heating, hot water, and process heat, including air conditioning and cooling), it shrinks from a present 5133 PJ/yr (2010) to about 2800 PJ/yr in the year 2050, thus dropping by 45%. At 67%, the heat demand of the commercial and institutional sector drops the most, followed by private households at 47%, and industry at 27%. This illustrates the smaller potentials for savings in the process-heat field, compared to the space-heating field. While private households currently have the greatest demand for heat (2330 PJ/yr), in 2050, industry will be the greatest consumer of heat, at 1276 PJ/yr at that time.

The scenarios represent three basically different **paths of development of the energy media used in transportation**. Besides the direct feedback effect on the demand for electricity, this also affects the supply infrastructure needed. In all three variants, an optimistic assumption about the growth of electromobility in the automobile sector is made, with the share of fully electric vehicles and plug-in-hybrids reaching at least 50% of mileage by 2050. The requirement for a third renewable fuel for transportation, besides electricity from renewables and biofuels – as shown in Scenarios A, B, and THG95 – results in the long term from a limited potential for biofuels from sustainable sources of biomass (300 PJ assumed), and limits on the potential for the use of battery-powered vehicles with regard to their range, especially for commercial goods traffic. The plausibility of the three paths of development has been checked for the automobile sector with a vehicle-fleet simulation model (DLR model VECTOR 21).

In passenger transportation in general, only slight structural **changes in mileage** are assumed. After 2030, motorized private traffic drops, air traffic continues to increase significantly until 2030, and total passenger mileage drops by 6% from the 2008 figure by 2050. Road haulage increases by 42% from the 2008 figure by 2040, and thus substantially more than the GDP, at 26%. In agreement with what is said in the Energy Concept, it has been assumed that the volume of goods haulage by rail can be doubled if the necessary investments in infrastructure are made in time.

The **expansion and flexibilization of cogeneration (CHP)** forms an important element in the transformation of the energy system. As part of this study, a detailed scenario of the development of combined-heat-and-power in Germany has been prepared. In order to ensure a high proportion of cogeneration in the electricity grid and the district-heating grids, while the share of wind and solar power increases, greater flexibility of the CHP plants is needed. This can be achieved by construction of heat storage facilities and higher installed capacities relative to the annual maximum heating load. Due to the future dominance of the fluctuating share from renewables, the desired substantial drop in the demand for heat, and the spread of solar collectors and geothermal CHP plants, the future share of fossil-fuelled cogeneration in electricity generation will probably be less than is assumed in general assessments of the potential.

For public district heating, additional **exploitable heat potentials** in the housing and commercial and institutional sector are seen. Based on a present consumption of about 380 PJ, a potential of 500 PJ can be exploited in the scenario by 2020; but after that, it will drop to about 350 PJ/yr, due to the increasing energy efficiency of the building stock. In industry, an additional heat-sink potential for process heat up to 350°C of 450 PJ/yr is taken into account. Due to increasing power-to-heat ratios, the generation of electricity from CHP increases in all scenarios from 85 TWh/yr at present to 137 TWh/yr in 2025 **(Figure 2).** As renewables continue to expand, the contribution of fossil-fuel CHP to overall CHP electricity generation of 110 TWh/yr in 2050 sinks to about 40%. In 2050, the existing gas-fired CHP installations will be partly fuelled with hydrogen or methane produced by renewable sources of energy.

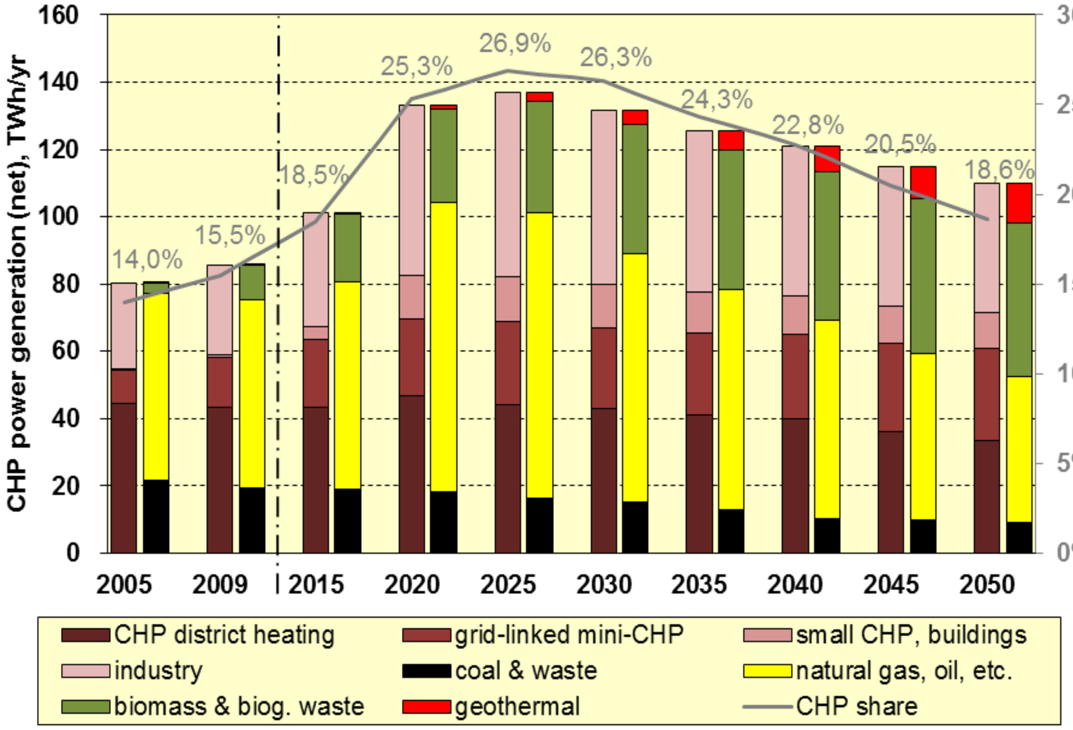


Figure 2: Trends of net CHP electricity generation by field of use and fuel, and share in total generation

The **limited potential of biomass as a source of energy** requires very resource-efficient handling. One important precondition is the definition of clearly specified environmentally restricted potentials, which take into account above all the competition with food production and with nature conservation, and possible environmental effects of the cultivation of fuel plants. According to earlier estimates of the environmentally “compatible” domestic potential for use of biomass, in Germany biomasses with a (primary) energy content of at most about 1550 PJ/yr are available for sustainable usage for energy purposes (including residues with at most 800 PJ/yr). The domestic land area usable for sustainable cultivation of energy plants is assumed to be 4.2 million hectares, of which at most 2.3 million ha are intended to be used to provide biofuels. Furthermore, substantial expansion of short-rotation fuel-wood plantations to an area of roughly 1 million ha is assumed. In the break-down of usage of biomass for energy selected here, with priority for efficient stationary usage, 60 TWh/yr (215 PJ/yr) of electricity, 630 PJ/yr of usable heat, and 300 PJ/yr of biofuels are produced, that is, a total of **1145 PJ/yr of final energy**. These quantities are largely exploited by 2030 in the scenarios. Since the global potential of biomass that can be utilized sustainably is estimated at only about 100 EJ, substantial import of biomass is not a sustainable strategy. Therefore, no (net) imports of biomass used for energy are assumed in this study.

The gaseous **chemical energy media hydrogen (H_2) and methane (CH_4)** can enable large amounts of electricity from renewables to be utilized for other types of consumption, as well. If very extensive supply from renewable sources of energy is to be achieved, then the use of hydrogen or methane from renewables – especially in view of the limited potentials for biomass and limited direct applications for electricity from renewables – will play a key role in reconversion to electricity to cover a residual load, in the generation of high-temperature heat, and in replacing fossil fuels for transportation. Both paths of usage, H_2 and CH_4, begin with hydrogen generated electrolytically by electricity from renewables. In a further process stage (methanation), this can be converted to synthetic methane. Since losses are unavoidable in the provision and utilization of H_2 and CH_4, it is obvious that all processes for direct utilization of electricity from renewables should be exploited to the full in the heat and transportation fields first.

For an economic evaluation of the use of hydrogen and/or methane as a **long-term storage medium for electricity**, a comparison must be made with other options for storing electric power, such as pumped-storage power plants and compressed-air storage. However, only chemical energy carriers can provide storage capacities of several hundred gigawatt-hours. Storage costs for electricity are generally high, ranging from 5 to 10 ct/kWh_{el} for pumped storage to 23 to 40 ct/kWh_{el} for compressed-air storage. The costs for hydrogen storage systems with a central electrolyser and electricity generation in a combined-cycle power station are inside this range, at 25 ct/kWh_{el} (present) to 10 ct/kWh_{el} (future), but have the lowest efficiency, at barely 40%.

In the case of the **use of H_2 and/or CH_4 as a fuel**, a comparison with the future prices of the competing fossil fuels is necessary. The cost of hydrogen depends mainly on the price of electricity, the investment costs and the utilization factor of the electrolysers. In 2050 **(Figure 3)**, hydrogen from renewables can be produced at filling stations with decentralized hydrogen generation, at electricity costs of around 4 ct/kWh, that is considerably cheaper than fossil fuels, even at utilization of less than 2,000 hours per year. Economically viable supply of the heat market by hydrogen from renewables will also be possible then.

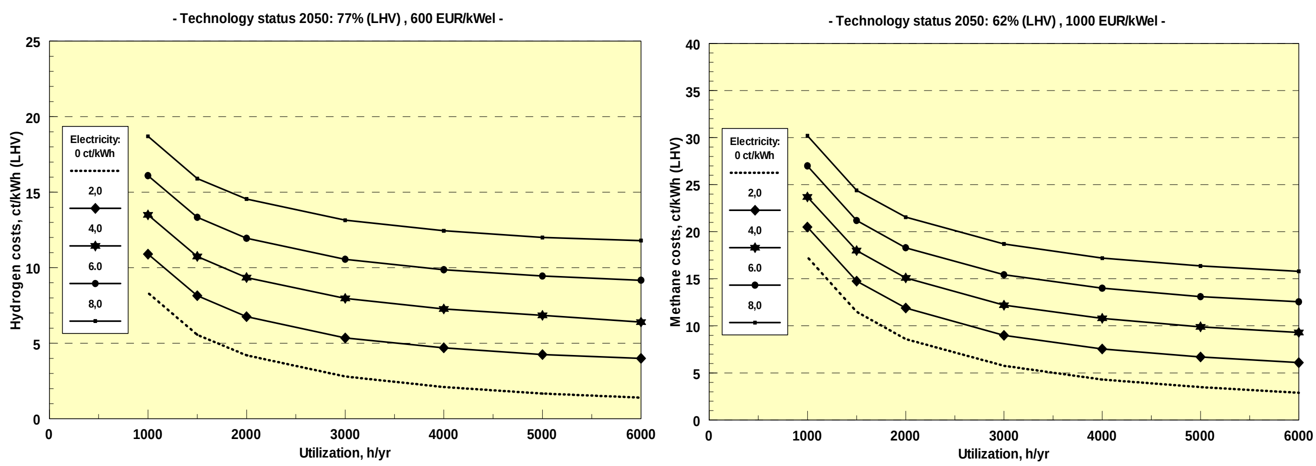


Figure 3: Hydrogen and methane production costs (in 2009 prices) in 2050, depending on utilization factor and electricity costs; 6% annual interest, amortization over 20 years, operation & maintenance 2% of capital costs per year

Depending on the price of electricity and the utilization factor, the costs of methane from renewables are 35% to 60% higher than those of hydrogen from renewables. But since the natural-gas infrastructure can be utilized fully in the case of methane, this cost disadvantage becomes less important. The opportunities for using these energy carriers, from a technical, structural, and economic point of view, will need to be compared in more detail in further studies, in the context of the overall costs of a complete energy supply from renewables. As seen at present, both options must be developed further and demonstrated locally, since they may play an important role in the long term.

4 Essential results of the 2011 A scenario

On the basis of the 2011 A scenario, which is the middle variant of the three “main scenarios” with respect to energy demand and the pathway of expansion of renewables, the transformation process of the power-supply system in Germany to a sustainable structure with only minor greenhouse-gas emissions is shown here as an example.

By 2050, there are substantial changes in the field of conversion to be seen **(Figure 4)**. The high conversion losses are reduced considerably by the expansion of electricity generation from renewables, and the increase in the proportion of cogeneration.

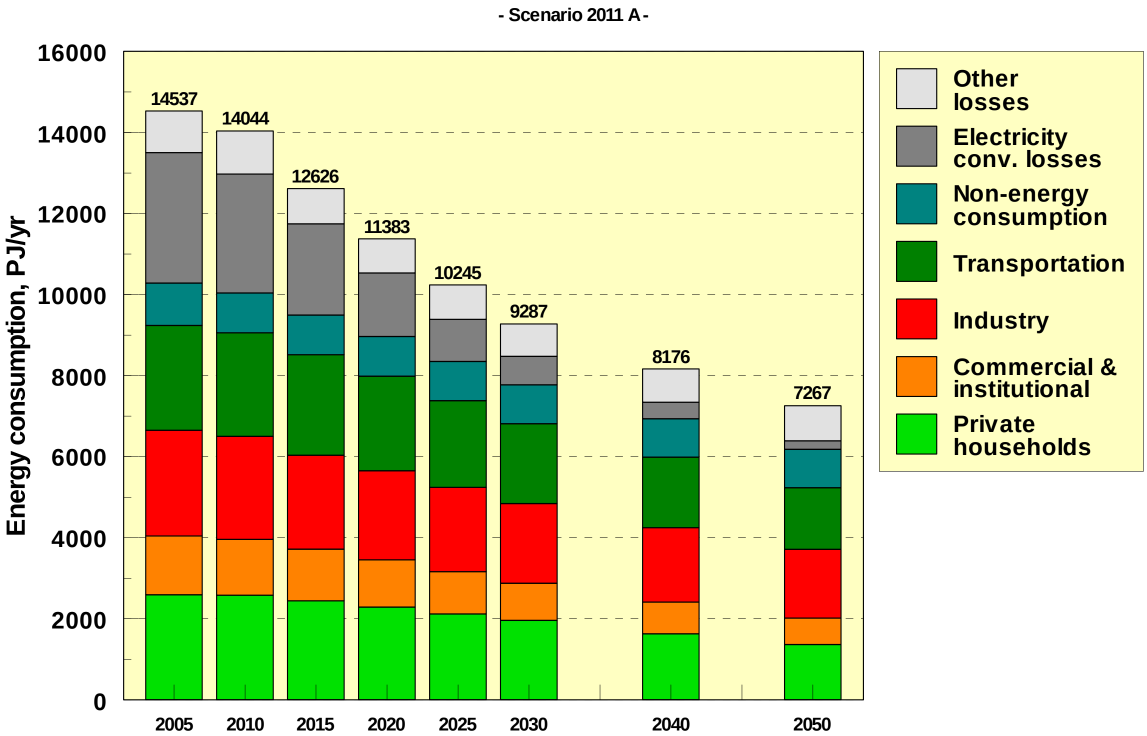


Figure 4: Development of final-energy consumption by sector, and of consumption in conversion (total = primary energy) in Scenario 2011 A

The share of pure condensing power stations in the total electricity production sinks in Scenario 2011 A from a current 74% (fossil and nuclear) by 2020 to 42%, and to 21% by 2030. In 2050, of the electricity from such sources, only that from flexible gas-fired power stations for the provision of guaranteed capacity is still significant. The other fossil-fuel power stations (coal and gas) are used for cogeneration. After 2025, the main contribution to electricity generation comes from renewables. This development – in addition to the increases in efficiency among end-users – contributes to the **substantial decrease in consumption of primary energy**. Primary-energy consumption in Scenario 2011 A sinks by 2050 to 52%. Final-energy consumption sinks somewhat less, still amounting in 2050 at 5236 PJ/yr to 58% of the value in 2010 (9060 PJ/yr). Final-energy consumption drops more than the average in the sectors of commercial and institutional use (-52%) and of private households (-48%), because of the large efficiency potentials in space heating. In transportation, final-energy consumption drops by 40%, and in industry by 33%.

In 2050, imports of fossil-fuel energy, at barely 3400 PJ/yr, will amount to 34% of the present quantity, making an import ratio of 46% at that time (present import ratio: 72%). These will then be almost equal shares from petroleum and natural gas; there will be barely any need for coal imports any more. In addition, there will be an imported contribution by renewables from the European electricity grid of 223 PJ/yr (corresponding to 62 TWh/yr of electricity). Thus the overall import ratio will be almost 50%. The contribution of imported energy from renewables to the total consumption of primary energy will be small, at 3% (11% of electricity consumption). In the future, it will be necessary to use natural gas more for electricity generation (an increase from a present roughly 900 PJ to 1150 PJ in 2025), due on the one hand to the increased demands for a more flexible set of conventional power stations, and on the other hand to its lower CO_2 emissions, compared to coal firing. If the potential for savings of natural gas in the field of space heating is exploited at the same time, the total demand for natural gas will remain roughly constant until 2025, and by 2050, the **demand for natural gas will be halved, compared to the current demand.**

In the Scenario 2011 A, 625 million metric tons of carbon dioxide per year will be avoided by 2050 (compared to 2010). Of this, 343 million tons CO_2/yr is due to increases in efficiency, and 282 million tons CO_2/yr due to the further expansion of renewables. Thus an **85% CO_2 reduction** over 1990 levels is achieved. So both the efficiency strategy and the renewables-expansion strategy must be implemented fully in order to create a climate-friendly energy supply in time and permanently. Of the reduction achieved by 2050, electricity generation provides 42%, the heat sector 39%, and the transportation section 19%. The **total greenhouse-gas emissions** drop in Scenario 2011 A by 2050 (compared to 1990) **by 81%** (in Scenario 2011 C by 82%).

The individual fields of use contribute in differing degrees to the **share of renewables in the energy supply (Table 1)**. In 2020, the renewables cover 41% of gross electricity consumption (or 47% of final-energy consumption in the form of electricity), 18.4% of the demand for heat as final energy (without the share of electricity), and 11.8% of the total demand for fuel. In 2030, the share of renewables in gross electricity consumption is also already 63%. By 2050, the transformation of the energy-supply system is well advanced. Of the gross electricity consumption, 85% is supplied from renewables, and a good half (52%) of the demand for heat, as well as 42% of the demand for fuel (excluding electricity) in transportation.

The substantial **growth trends for renewables** since the beginning of this century must continue without weakening **(Figure 5)**. Only after 2030 do they weaken somewhat. By 2020, their contribution to final energy almost doubles, compared to 2010, to 1822 PJ/yr. By 2050, it increases to over three times the quantity of energy in 2010, at 3073 PJ/yr. At first, the contribution of biomass remains dominant; in 2030, its share of the total final energy from renewables still amounts to 46%. After this, its potentials are fully exploited, while the growth of the other renewables continues. Wind power increases its contribution to final energy continuously, reaching a share of 28% in 2050, at 800 PJ/yr. In the long term, solar radiation becomes the main growth factor. While its contribution is currently still small, at 5%, in 2050 its contribution is comparable to that of wind power. The contribution of geothermal energy (including heat pumps) grows to 13% by 2050. In that year, the various renewable sources of energy make a much more balanced contribution to the energy mix than is presently the case, with the dominance of biomass.

Table 1: Principal data of Scenario 2011 A, in particular contributions by and shares of renewables

	2008	2009	2010	2020	2030	2040	2050
Primary energy, PJ/yr [1]	14216	13427	14044	11383	9287	8176	7267
Primary energy renewables, PJ/yr [1]	1147	1201	1322	2270	2969	3483	3840
Share of RE in PE usage, %	**8,1**	**8,9**	**9,4**	**19,9**	**32,0**	**42,6**	**52,8**
Share of RE in PE usage (w/o NE), %	**8,7**	**9,7**	**10,1**	**21,7**	**35,7**	**48,4**	**61,1**
Final energy, PJ/yr	9098	8691	9060	7991	6820	5992	5236
Final energy renewables, PJ/yr	849	903	992	1822	2431	2827	3073
Share of RE in FE usage, %	**9,3**	**10,4**	**11,0**	**22,8**	**35,6**	**47,2**	**58,7**
Share of RE in GFEC [2], %	***9,0***	***10,0***	***10,6***	***22,0***	***34,3***	***45,5***	***56,5***
Electric final energy, PJ/yr	1886	1782	1859	1742	1619	1526	1415
Electric final energy renewables, PJ/yr	336	341	372	820	1094	1197	1214
Share of renewables, %	**17,8**	**19,1**	**20,0**	**47,1**	**67,6**	**78,4**	**85,8**
Heat final energy, PJ/yr [3]	4701	4429	4703	3999	3377	2912	2517
Heat final energy renewables, PJ/yr	381	441	491	736	977	1157	1317
Share of renewables, % *)	**8,1**	**10,0**	**10,4**	**18,4**	**28,9**	**39,7**	**52,3**
Fuel final energy, PJ/yr [4]	2511	2480	2498	2249	1824	1554	1304
Fuel final energy, renewables, PJ/yr	132	121	129	266	360	473	542
Share of renewables, % **)	**5,3**	**4,9**	**5,2**	**11,8**	**19,7**	**30,4**	**41,6**
Gross electricity consumpt., TWh/yr [5]	615	578	610	573	558	572	584
Generation from renewables, TWh/yr [6]	93	95	103	235	351	434	496
Share of renewables, %	**15,2**	**16,4**	**16,9**	**40,9**	**62,9**	**75,8**	**84,9**
Share of renewables, domestic, %	15,2	16,4	16,9	40,7	59,5	67,7	74,3
Primary energy, PJ/yr	14216	13428	14044	11383	9287	8176	7267
Renewable sources of energy	**1147**	**1201**	**1322**	**2270**	**2969**	**3483**	**3840**
Petroleum	4904	4635	4678	3534	2704	2271	1740
Coal [7]	3485	3184	3435	1625	935	505	166
Natural gas, petroleum gas, mine gas	3058	2937	3075	3223	2679	1917	1520
Fossil-fuel energy, total	**11447**	**10755**	**11188**	**8382**	**6318**	**4693**	**3427**
Nuclear power	1622	1472	1534	731	0	0	0
CO_2 emissions, millions of tons/yr	**797**	**745**	**779**	**521**	**365**	**249**	**154**
Reduction since 1990, % [8]	**20,3**	**25,5**	**22,1**	**47,9**	**63,5**	**75,1**	**84,6**
Avoided due to RE, M of tons CO_2/yr	109	110	115	220	303	361	396
GHG emissions, M of tons CO_{2eq}/yr [9]	**988**	**911**	**943**	**644**	**466**	**337**	**229**
Reduction since 1990, %	18,4	24,8	22,1	46,8	61,6	72,2	81,1

***) Share of RE heat, AGEE-Stat/EEWärmeG, %**	**7,6**	**8,9**	**10,2**	**16,4**	**25,9**	**35,3**	**46,1**
****) Share of RE final energy transport, %**	**5,5**	**5,1**	**5,4**	**13,7**	**24,8**	**37,2**	**49,4**

1) Primary energy (PE) by the physical energy content method; incl. RE but without non-energy (NE) consumption

2) Gross final-energy consumption (GFEC) = final-energy (FE) consumption plus grid losses and own consumption of heat and electricity in power and combined-heat-and power stations

3) Only fuels, i.e. without electricity, used to provide heat. AGEE-Stat and EEWärmeG define the share of renewable final energy for heat without electricity related to the total final energy demand for heat incl. electricity, see *)

4) Fuel consumption for road, rail, navigation, and air transportation, without electricity used

5) Gross electricity consumption, with electricity from pumped-storage facilities, from 2030 on including power for generating hydrogen from renewables

6) Including renewable-source electricity from hydrogen

7) Including other fossil fuels, including balance of trade in fossil/nuclear-powered electricity

8) 1990 = 1,000 million t CO_2/yr (energy-related emissions and blast-furnace process)

9) Including changes in land use (LULUCF; 1990 = 1211 million t CO_2eq/yr)

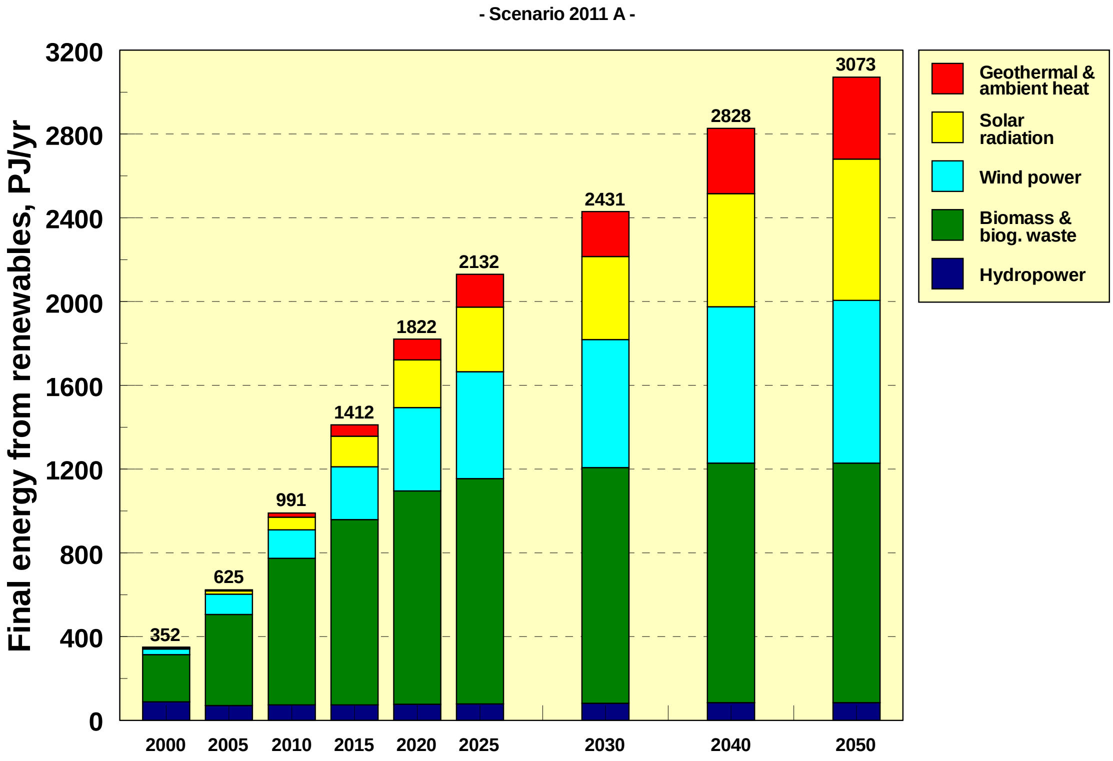


Figure 5: Contribution to final energy (electricity, heat, motor fuels) of renewables by source in Scenario 2011 A (data until 2010 from [AGEE-Stat 2011]; as of July 2011)

The contribution of renewables to the electricity supply increases from 103.5 TWh/yr in the year 2010 to 235 TWh/yr in 2020 and 490 TWh/yr in 2050 **(Figure 6)**. In the longer term, the growth factors for renewables are mainly wind power and solar radiation (photovoltaic and solar-thermal electricity from Southern Europe and North Africa), while the potential of biomass is fully exploited at around 60 TWh/yr. At 13.5% per year, photovoltaic power grows most rapidly in the period until 2020, followed by wind power (average growth rate until 2020: 11% per year)[1].

Between 2020 and 2050, provision of electricity from renewables grows continuously, with an average growth rate of 2.5% per year. Expansion of generation from geothermal sources begins relatively slowly, and plays a fairly minor role until 2050 in the scenario. The decisive aspect of this is uncertainty about its wider implementability as a generating technology.

For electricity generation from renewables overall, importing electricity from renewables also begins to play a role from about 2020 on. This is based on the assumption that the transformation of the electricity supply to renewable sources must become a common European

[1] The annual increase in photovoltaic capacity from 2012 on in the 2011 scenarios is based on the previously intended target corridor of the Renewable Energy Sources Act (EEG): after the current peak in expansion declines, a target corridor of 2,500 to 3,500 MW/yr is assumed (cf. Table 2: Installed PV capacity in 2020: 53.5 GW). Thus it also corresponds roughly to the development path within the National Action Plan (NREAP). And after 2020, the scenarios assume a significantly smaller PV expansion (including replacements) compared to 2010-2011. For the scenario analysis, it was not possible to take into account the amendments to the photovoltaic tariffs in the EEG presented in February 2012. It is hardly possible to quantify the effects on the German photovoltaic market of these changes at the moment. The very rapid and substantial reduction of PV feed-in tariffs provided for in the current amendment could lead to a reduced expansion of photovoltaics, compared to the scenarios, in the short term (until about 2016). If the reduction in the costs of new PV installations intended by this can be achieved, stable PV growth in the medium and long term is still possible, since PV installations even without EEG feed-in-tariff will then be possible (grid parity achieved). However, a strong shrinkage of the PV market which exceeds the assumptions of the scenarios, would make a change in the spectrum of generation from renewables necessary (e.g. more wind power), in order to achieve the longer-term expansion targets.

goal within the foreseeable future. Only in this way can an optimum renewables-based electricity supply be set up structurally and economically. Since very large potentials for renewables, that can be exploited inexpensively, exist outside Germany, the assumption of **increasing imports of electricity from renewables** on balance over the longer term is obvious. In 2030, on balance only 5.5% of the electricity from renewables is imported (19 TWh/yr); by 2050 it is almost 13% of generation from renewables (11% of the consumption of electricity), at 62 TWh/yr. The contribution of fluctuating generation (wind, photovoltaic) is a mere 8% of overall gross electricity consumption at present. By 2020, it grows to 28%, and by 2050 to 55%.

By 2020 already, the **installed capacity of renewables** at 117 GW, is considerable greater than the expected maximum grid load of about 80 GW. With 97 GW capacity, the share of the fluctuating sources of energy wind and solar radiation dominates (**Table 2**). At that point in time, the photovoltaic capacity exceeds the entire installed capacity of wind power, but only generates 40% of the amount of electricity of wind power. The high installed capacity of fluctuating renewable sources demonstrates the sharply growing need for balancing and storage options by 2020 at the latest. For this reason, growth of international grid connection and of "domestic" off-shore wind power is emphasized in the scenario after 2030, while the growth of domestic PV capacity slackens off in the long term. The installed capacity of renewables grows to a total of 179 GW, if the proportional capacity of imports of energy from renewables is taken into account. In Scenario 2011 A, about 40 GW of this (110 TWh/yr) is intended for the provision of hydrogen from renewables as a storage medium and as a fuel, which is consumed by electrolysers according to the supply of power from renewables.

Because of the considerable expansion of renewables, the **utilization of fossil-fuel power stations** drops from an average of 4600 hours per year in 2010 to 3700 h/yr in 2020; after that, the decline becomes even greater (2030: ca. 3300 h/yr: 2050: ca. 2200 h/yr).

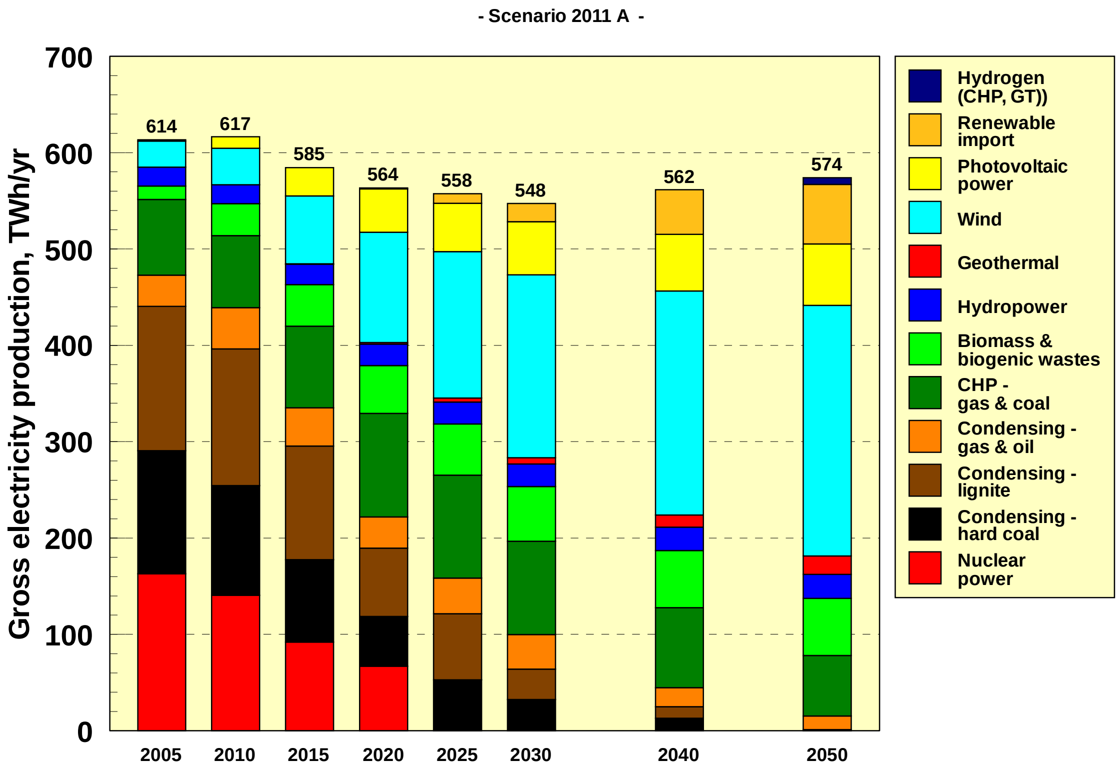


Figure 6: Structure of gross electricity generation in Scenario 2011 A

Table 2: Installed generating capacity from renewable sources in Scenario 2011 A (capacities at end of each year)

in GW *)	2000	2005	2010	2015	2020	2025	2030	2040	2050
Hydroelectric	**4.24**	**4.33**	**4.40**	**4.51**	**4.70**	**4.80**	**4.92**	**5.09**	**5.20**
Wind power	**6.1**	**18.4**	**27.2**	**36.9**	**49.0**	**58.1**	**67.2**	**77.5**	**82.8**
- on-shore	6.1	18.4	27.1	33.9	39.0	41.4	43.7	48.0	50.8
- off-shore	-	-	0.09	2.94	10.0	16.7	23.5	29.5	32.0
Photovoltaic **)	**0.076**	**1.98**	**17.3**	**38.5**	**53.5**	**57.3**	**61.0**	**63.3**	**67.2**
Biomass	**1.17**	**3.12**	**6.34**	**8.08**	**8.96**	**9.48**	**10.00**	**10.38**	**10.38**
- Biogas, sewage gas, etc.	0.39	0.70	2.96	3.63	3.72	3.90	4.16	4.45	4.45
- solid biomass	0.19	1.21	2.03	2.83	3.54	3.88	4.14	4.23	4.23
- biogenic waste	0.59	1.21	1.35	1.62	1.70	1.70	1.70	1.70	1.70
Geothermal	**-**	**-**	**0.01**	**0.08**	**0.30**	**0.65**	**1.00**	**1.94**	**2.95**
EU power grid	**-**	**-**	**-**	**-**	**0.35**	**1.98**	**3.60**	**8.15**	**10.45**
- solar-thermal plants	-	-	-	-	-	-	1.20	5.15	6.55
- wind & other renew.	-	-	-	-	0.35	1.98	2.40	3.00	3.90
Total renew.power	**11.57**	**27.85**	**55.27**	**88.1**	**116.8**	**132.3**	**147.8**	**166.3**	**179.0**

*) Data until 2010 from [AGEE-Stat 2011], as of July 2011 **) for 2015 and 2020 cf. footnote 1

In the longer term, however, the average capacity utilization of renewable generation increases, because of the substantial growth of off-shore wind farms and the importing of electricity from renewables from regions with favourable supply characteristics. In 2020, it is about 2100 h/yr, and reaches a value of 2750 h/yr in 2050. This demonstrates a certain **evening-out of the supply from renewables**, which makes its integration into the power supply system easier.

Generation in large power stations without utilization of the waste heat, which is still dominant today (70% of gross generation in 2010) gives way in Scenario 2011 A to an electricity supply structure based mainly on decentralized generation from renewables. And the **installed capacity of the fossil-fuel condensing power stations** also changes accordingly. The capacity of pure fossil-fuel condensing power stations drops from a current 65 GW to 49 GW in 2020, and to 39 GW in 2030. The capacity of fossil-fuel CHP plants, on the other hand, increases to a good 28 GW by 2030. In the scenario, a total of 36 GW of older fossil-fuel power stations are closed down or transferred to cold reserves by 2020. 20 GW of this consists of old hard-coal power stations, 12 GW of old lignite power stations, and 4 GW of old natural-gas-fired gas turbines or combined-cycle power stations. Building of new fossil-fuel power stations must be restricted, at about 27 GW (of which 8 GW large CHP and 4 GW mini CHP). Apart from those already under construction now, no new coal-fired power stations come into operation in Scenario 2011 A. However, another 9 GW of new gas-fired capacity is needed by 2030. On balance, in 2030 the capacity of **gas-fired power plants (including mini CHP plants) is 10 GW higher than today** in 2030. In total, in Scenario 2011 A a good 70% of the current fossil-fuel power plant capacity is out of operation by 2030. In 2050, a total fossil-fuel-fired capacity of 38 GW remains.

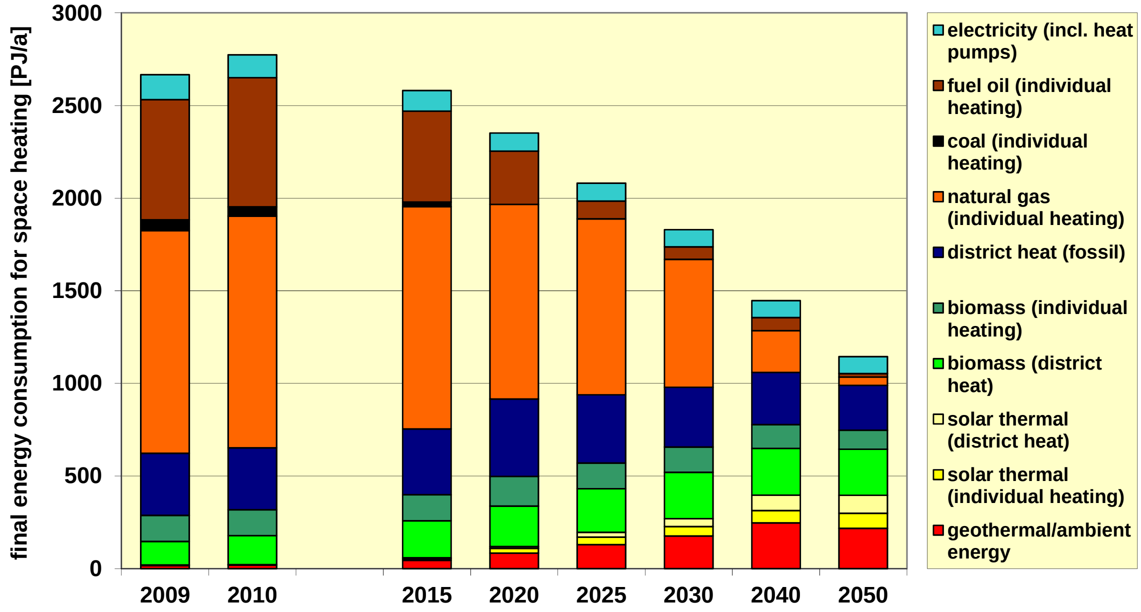


Figure 7: Final-energy use for space heating in Scenario 2011 A (including electricity used for space heating)

The **consumption of fossil fuels to generate heat** drops continuously until 2050, especially for space heating **(Figure 7)**. While in 2009 a total of 3933 PJ fossil-fuel final energy (including district heating schemes, supply to buildings and industrial CHP, excluding electricity generated from fossil fuels) was consumed to generate heat, this amounts drops by 70%, to 1160 PJ, in 2050. Natural gas is still used to a significant extent to provide process heat and electricity in cogeneration in that year.

The **use of renewables to provide heat** almost triples, from a current 490 PJ to more than 1300 PJ in 2050. Renewables then cover **53% of final-energy consumption** for heating (excluding the use of electricity to generate heat). This trend and the dynamics of growth on which it is based require a fundamental change in the market situation, and subsidy incentives that are sufficient over the long term in the heating sector. For the provision of heat from individual units, an average annual growth rate until 2030 of 8.3% for heat pumps, and of 9.7% for solar collectors, is assumed. In the scenario, the segments of district heating with solar collectors and geothermal sources, which are little developed as yet, grow at considerably higher rates. Deep geothermal sources grow at 18% per year until 2030, while local solar-heating networks even grow at 22% per year. The annually installed capacity of renewables for heat production (new additional installations and replacement of old installations) runs at about 5.5 GW_{th}/yr at present. For 2020, a capacity of 9.4 GW_{th} to be installed annually is expected. The replacement of older renewables facilities plays an increasingly important role from 2020 on, so that in 2030 almost 12 GW_{th}/yr of thermal renewable-powered facilities, and in 2050 more than 17.6 GW_{th}/yr are installed.

The **use of renewable sources of energy in transportation** reaches a proportion of 14%, at 321 PJ/yr, by 2020. It grows to almost 50% in 2050, at 752 PJ/yr **(Figure 8)**. The use of fossil fuels does drop considerably, but due to the use of diesel fuel for heavy goods traffic and the demand for kerosene for air transportation, there remains a significant consumption of about 760 PJ in 2050. In that year, not more than 300 PJ/yr of biofuels are used, and not more than 242 PJ/yr of hydrogen from renewables. By 2050, more than a third of the potential for biofuels is allocated to air traffic, in the form of synthetic biofuels (BtL = biomass to liquid).

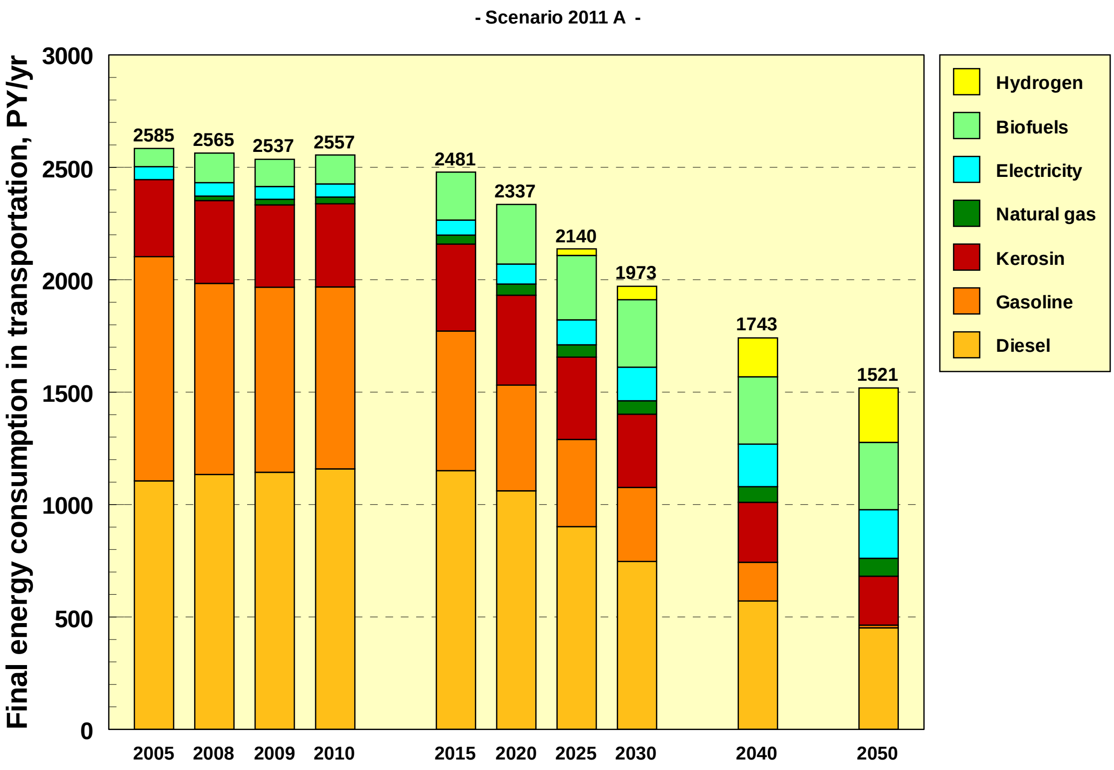


Figure 8: Final-energy use for transportation in Scenario 2011 A

Electricity consumption for electromobility already comes to 21 TWh/yr in the year 2020, and reaches 44 TWh/yr in 2050. For 2020 and 2030, the targets of one million and six million electric-powered motor cars and light commercial vehicles in the fleet scenario are reached. The very broad use of electric vehicles and hydrogen-powered drives requires an additional consumption of electricity in 2050 amounting to 44 TWh/yr for electromobility and 87 TWh/yr for hydrogen, which is provided entirely from renewables. About 50 GW of capacity from renewables are required to generate this amount of electricity.

5 Essential results of the comparison of the scenarios

In Scenarios 2011 A, B and C, **differing developments of the fleets of vehicles**, and thus of the energy carriers used, are represented. In Scenario 2011 C, there is the smallest final-energy consumption for transportation in 2050, 1380 PJ (compared to 1521 PJ/yr in Scenario A), and also the greatest reduction in CO_2 in transportation, due to the major role of efficient electric propulsion. Scenario 2011 B has the highest final-energy demand in 2050, of 1565 PJ, due to the higher specific consumption of gas engines compared to hydrogen-powered fuel cells. In Scenario 2011 C, about 80 TWh of electricity are used for electric-powered vehicles for all road transportation in 2050.

The comparison of the scenarios shows that, from today’s perspective, fossil fuels can be substituted for in transportation in widely differing ways, each with its own advantages and disadvantages or limits. In other scenario studies, much higher consumption of biofuels and of biomass overall is sometimes assumed, which requires large imports of biomass to occur in 2050 **(Table 3)**. But because of the limited worldwide potential amounts of biomass that can be utilized sustainably, the assumption of massive biomass imports for use as biofuel is not a robust strategy.

Table 3: Comparison of coverage of energy demand in transportation (in PJ/yr) in 2050 and of the total biomass for all uses with scenarios from other studies

Year 2050	Fossil fuels	Bio-fuels	Renewable hydrogen	Renewable methane	Electro-mobility	Railway electricity	FEC transport	Total biomass**)
Scenario 2011 A	763	300	**242**	0	158	59	**1521**	1550*)
Scenario 2011 B	782	300	0	**266**	158	59	**1565**	1550*)
Scenario 2011 C	731	300	0	0	**290**	59	**1379**	1550*)
WWF Innovation	436	921	10	not given	101	86	**1560**	1720
McKinsey & Company [BMU 2010]	~980	~80	not given	not given	~250	~90	**~1400**	~500
Scenario I B [EWI 2010]	492	772	15	not given	144	~90	**1512**	2154
communication: 2010	2369	129	0	0	0	59	**2557**	958

*) sustainable domestic primary-energy potential FEC = Final-energy consumption
**) consumption including biomass use for electricity and heat generation

The transportation sector must also provide a substantial reduction in emissions, compared to the other sectors of consumption. In a scenario that is in line with the targets, the limitation of the biofuel potential thus makes it necessary both to strive for a very extensive use of battery-powered electric vehicles, and to consider the introduction of a third renewable fuel. This is necessary especially if the transportation sector is to be based largely on renewables in the longer term.

The different strategies in the transportation sector also lead to changes in the overall **final-energy and primary-energy structure of the respective scenarios**. By comparison with Scenario 2011 A, the wide establishment of electromobility and the dispensing with hydrogen as a fuel assumed in Scenario 2011 C results in a substantially lower gross electricity consumption in 2050 (Scenario 2011 C: 534 TWh/yr; Scenario 2011 A: 584 TWh/yr in 2050; Scenario 2011 B: 622 TWh/yr) and a smaller overall final-energy demand (Scenario 2011 C: 5100 PJ/yr; Scenario 2011 A: 5236 PJ/yr in 2050). Thus the CO_2 output, at 147 million t/yr, is also lower in 2050 (Scenario 2011 A: 154 million t/yr). The more favourable energy characteristic values of Scenario 2011 C, compared to Scenarios A and B **(Table 4)**, mean that, for reasons of efficiency and climate protection, a **large proportion of electromobility in the transportation sector must be sought.** Therefore, by 2050 the proportion of electric vehicles among motor cars should exceed 50% if possible, and trend clearly in the direction of Scenario 2011 C.

In **Scenario A',** because of the rather disappointing experience to date with cutting back the electricity demand, the reduction target of the Energy Concept is applied exclusively to the "conventional" consumers (i.e. without heat pumps and electromobility). The final-energy consumption of these electricity consumers is therefore "only" reduced to 387 TWh/yr by 2050, instead of 335 TWh/yr (Scenario 2011 A, which is also a considerable reduction. The additional electricity consumption is compensated for by increased expansion of the renewables, in order to achieve a reduction of greenhouse-gas emissions of 80% by 2050 despite this. Thus in this scenario, generation of electricity from renewables amounts to 544 TWh/yr instead of 496 TWh/yr (Scenario 2011 A), and the share of renewables in generation reaches 85.5%.

Table 4: Principal data of Scenario 2011 C, in particular contributions by and shares of renewables

	2008	2009	2010	2020	2030	2040	2050
Primary energy, PJ/yr [1)]	14216	13428	14044	11367	9137	7899	6993
Primary energy renewables, PJ/yr [1)]	1147	1201	1322	2278	2994	3418	3695
Share of RE in PE usage, %	**8.1**	**8.9**	**9.4**	**20.0**	**32.8**	**43.3**	**52.8**
Share of RE in PE usage (w/o NE), %	**8.7**	**9.7**	**10.1**	**21.8**	**36.7**	**49.4**	**61.4**
Final energy, PJ/yr	9098	8691	9060	7935	6696	5829	5099
Final energy renewables, PJ/yr	849	903	992	1831	2477	2828	3015
Share of RE in FE usage, %	**9.3**	**10.4**	**11.0**	**23.1**	**37.0**	**48.5**	**59.1**
Share of RE in GFEC [2)], %	**9.0**	**10.0**	**10.6**	**22.2**	**35.6**	**46.8**	**57.0**
Electric final energy, PJ/yr	1886	1783	1859	1786	1728	1674	1546
Electric final energy renewables, PJ/yr	336	341	372	829	1200	1374	1406
Share of renewables, %	**17.8**	**19.1**	**20.0**	**46.4**	**69.5**	**82.1**	**90.9**
Heat final energy, PJ/yr [3)]	4701	4428	4703	4000	3379	2911	2522
Heat final energy renewables, PJ/yr	381	441	491	736	977	1154	1310
Share of renewables, % *)	**8.1**	**10.0**	**10.4**	**18.4**	**28.9**	**39.6**	**51.9**
Fuel final energy, PJ/yr [4)]	2511	2480	2498	2149	1589	1244	1031
Fuel final energy, renewables, PJ/yr	132	121	129	266	300	300	300
Share of renewables, % **)	**5.3**	**4.9**	**5.2**	**12.4**	**18.9**	**24.1**	**29.1**
Gross electricity consumpt., TWh/yr [5)]	615	578	610	585	565	549	534
Generation from renewables, TWh/yr [6)]	93	95	103	237	358	419	462
Share of renewables, %	**15.2**	**16.4**	**16.9**	**40.5**	**63.2**	**76.3**	**86.6**
Share of renewables, domestic, %	15.2	16.4	16.9	40.3	59.9	70.5	78.7
Primary energy, PJ/yr	14216	13428	14044	11367	9137	7899	6993
Renewable sources of energy	**1147**	**1201**	**1322**	**2278**	**2994**	**3418**	**3695**
Petroleum	4904	4635	4678	3431	2524	2135	1758
Coal [7)]	3485	3184	3435	1625	935	443	155
Natural gas, petroleum gas, mine gas	3058	2937	3075	3302	2684	1903	1385
Fossil-fuel energy, total	**11447**	**10755**	**11188**	**8359**	**6143**	**4481**	**3298**
Nuclear power	1622	1472	1534	731	0	0	0
CO_2 emissions, millions of tons/yr	**797**	**745**	**779**	**518**	**352**	**232**	**147**
Reduction since 1990, % [8)]	**20.3**	**25.5**	**22.1**	**48.2**	**64.8**	**76.8**	**85.3**
Avoided due to RE, M of tons CO_2/yr	109	110	115	221	303	345	364
GHG emissions, M of tons CO_{2eq}/yr [9)]	**988**	**911**	**943**	**641**	**453**	**320**	**222**
Reduction since 1990, %	18.4	24.8	22.1	47.1	62.6	73.6	81.7

***) Share of RE heat, AGEE-Stat/EEWärmeG, %**	**7,6**	**8,9**	**10,2**	**16.4**	**25.9**	**35.2**	**45.8**
****) Share of RE final energy transport, %**	**5,5**	**5,1**	**5,4**	**16.0**	**29.2**	**39.4**	**46.5**

1) Primary energy (PE) by the physical energy content method; incl. RE but without non-energy (NE) consumption

2) Gross final-energy consumption (GFEC) = final-energy (FE) consumption plus grid losses and own consumption of heat and electricity in power and combined-heat-and power stations

3) Only fuels, i.e. without electricity, used to provide heat. AGEE-Stat and EEWärmeG define the share of renewable final energy for heat without electricity related to the total final energy demand for heat incl. electricity, see *)

4) Fuel consumption for road, rail, navigation, and air transportation, without electricity used

5) Gross electricity consumption, with electricity from pumped-storage facilities, from 2030 on including power for generating hydrogen from renewables

6) Including renewable-source electricity from hydrogen

7) Including other fossil fuels, including balance of trade in fossil/nuclear-powered electricity

8) 1990 = 1,000 million t CO_2/yr (energy-related emissions and blast-furnace process)

9) Including changes in land use (LULUCF; 1990 = 1211 million t CO_2eq/yr)

A comparison of Scenarios 2011 A and 2011 B permits a comparison of the **expenditures for the chemical storage** of large amounts of electricity from renewables by means of the two options hydrogen and methane from renewable sources of energy. Both scenarios are based on the same final-energy demand, and achieve the same reduction of CO_2 emissions. The consumption in the transportation sector differs between hydrogen-powered and methane-powered vehicles by 24 PJ/yr, and there are additional losses of 20% of the energy of the hydrogen in methanation. At present, it cannot be determined conclusively whether the extra expenditure of 38 TWh/yr of electricity from renewables for methanation in Scenario 2011 B, compared to Scenario 2011 A, is offset by the infrastructural advantages of methane compared to hydrogen. Since large-scale use of methanation will not be necessary for at least two decades, the development and engineering-structural and economic analyses required can be undertaken without being pressed for time.

The scenario representing a **95% reduction in greenhouse-gas emissions** (Scenario 2011 THG95) requires a practically complete energy supply from renewables for Germany. According to previous analyses with respect to a possible change in structure and speed of transformation of the energy supply, the date 2050 is an extremely challenging target; therefore, in the Scenario 2011 THG95, a greenhouse-gas reduction of 95% has not been assumed until 2060.

While in the year 2050 the share of renewables in gross electricity consumption is already around 85% in Scenarios 2011 A, B, and C, the share of renewables in the heat sector is only 52% to 54% at that time, and 47% to 50% in transportation.

Since a more extensive use of biomass is not justifiable from the point of view of sustainability, a further increase in the contribution from renewables can only be achieved by more intensive expansion of power generation from renewables **(Figure 9)** and the increased direct (electromobility, electricity for heating) or indirect (hydrogen or methane production with renewables) use of this electricity. A further increase in the direct production of heat from renewables by means of solar collectors and geothermal heat, beyond the volume assumed in Scenarios A, B, and C, is only possible to a very limited extent.

In order to reach an almost complete supply from renewables by 2060, a course to **electricity from renewables as "primary energy"** must be set earlier than was described in the scenarios for the goal of an 80% reduction in GHG emissions. This involves substantial new applications for electricity, compared to the present situation, which require 255 TWh/yr additional electricity from renewables, compared to the Scenario 2011 A, in 2050, and 420 TWh/yr in 2060. In total, in Scenario 2011 THG95 28% more final energy from renewables is provided in 2050 already than in Scenario 2011 A, amounting to 3,940 PJ/yr. This value rises to 4,560 PJ/yr by 2060. In 2050, the main support for the supply from renewables is wind power, with a contribution of primary energy of 1715 PJ/yr, followed closely by solar power, with 1620 PJ/yr. In this scenario, the energy-related carbon-dioxide emissions can already be reduced by 91%, and total GHG emissions by 86.5%, from 1990 levels by 2050.

The differing structural assumptions of the scenarios result in an **expansion corridor for electricity from renewables** in accordance with **Figure 9 and Table 5**. The comparison shows that additional potentials can be mobilized mainly from wind power and solar power, which have substantial technical potentials. In 2030, the range of utilization of "domestic" wind power (on-shore and off-shore) lies between 70 and 78 GW. It increases to 79 to 115 GW by 2050, and finally to 83 to 142 GW of installed capacity by 2060. This allows between 268 and 477 TWh/yr of electricity to be provided. Thus wind is the most important domestic source of energy. For solar cells, the maximum capacities range from 67 to 82 GW in 2050, and from 70 to 86 GW in

2060. In the long term, geothermal generation also contributes a substantial share; but its large-scale expansion does not occur until after 2030.

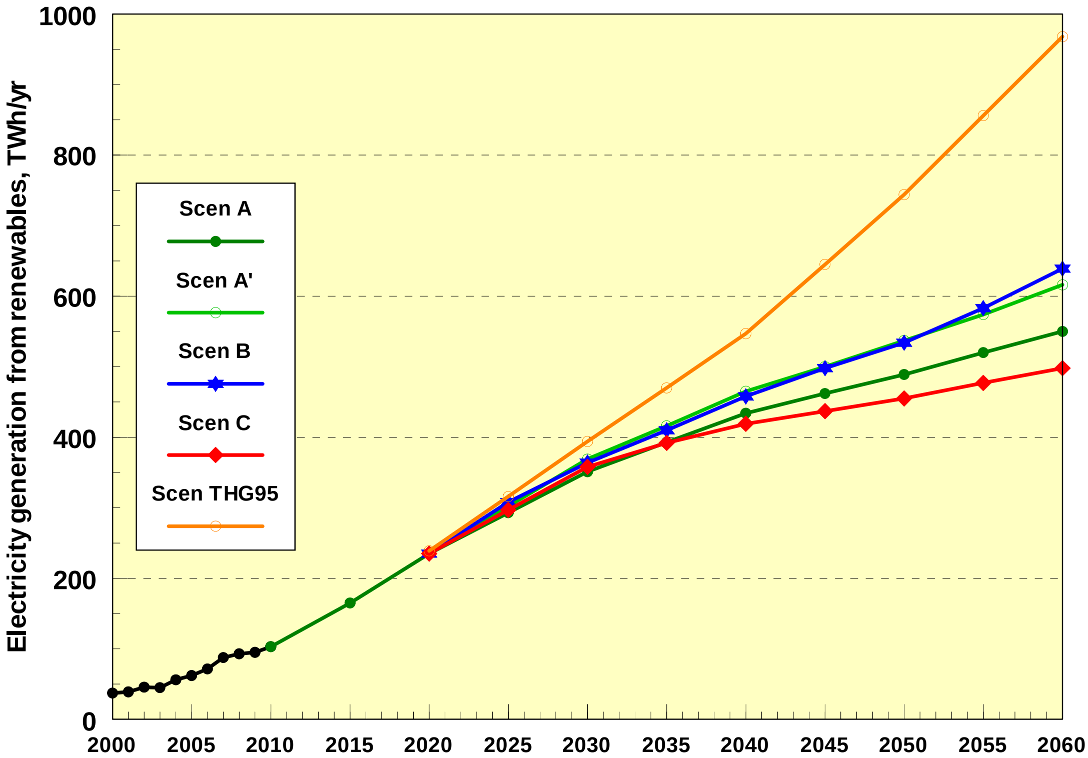


Figure 9: Range of generation from renewables in the 2011 scenarios

Table 5: Lower and upper limits of installed capacity from renewables

			Lower limit (Scenario C)				**Upper limit (Scenario THG95)**			
GW	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**	**2030**	**2040**	**2050**	**2060**
Hydro	4.4	4.7	4.9	5.1	5.2	5.3	4.9	5.1	5.2	5.3
Biomass	6.4	8.1	10.0	10.4	10.4	10.4	10.0	10.4	10.4	10.4
Wind**)	27.2	51.3	70.2	77.5	79.0	83.0	77.8	97.7	115.3	141.8
Photovoltaic	17.3	53.5	61.0	63.1	67.2	70.0	67.9	75.2	81.8	86.4
Geothermal	0.01	0.3	1.0	1.8	2.4	3.2	1.0	2.2	4.9	8.6
Renew. import*)	0	0.4	3.6	5.9	7.0	9.3	5.4	14.0	29.0	44.0
Total	**55.3**	**119.2**	**150.7**	**163.7**	**171.1**	**181.1**	**167.0**	**204.5**	**246.5**	**296.4**
Total, domestic	**55.3**	**118.8**	**147.1**	**157.8**	**166.1**	**171.8**	**161.6**	**190.5**	**217.5**	**252.4**

*) Balance of electricity imports, mainly wind power, with increasing share of solar-thermal power (CSP)
**) On-shore and off-shore installations

Of growing significance in the longer term is the integration of generation from renewables into an pan-European grid, since the objective of a complete change-over to renewable sources of energy assumed here cannot be achieved by one country alone, but requires a certain **"harmonization" of the transformation process** in the medium term. Only in this way can extreme structural and economic distortions in the European energy market be avoided, and a growing together of Europe be supported in this respect, as well. The contribution of imports of electricity from renewables can reach a share between 10% and 23% in 2050, and between 12% and 28% in 2060. In the maximum case, imports of renewables represent an output of 44 GW.

6 Load coverage and balancing measures in the electricity supply

At present, fluctuations in demand are balanced by the use of stored fossil and nuclear energy. In contrast, in a system with large shares of energy from renewable sources, fluctuations in supply caused by weather conditions need to be synchronized with the fluctuating demand for energy. This poses special challenges to the integration of renewables into the electrical energy supply system. The electricity sector of Scenarios 2011 A and C was studied in detail by means of the two models ‘REMix’ (DLR) and ‘Virtual Electricity Supply System’ (IWES) by simulations over time, some of them with spatial resolution, to validate the load coverage with balancing measures. In this way, it has been shown that – given the assumptions made concerning expansion of the grid, availability of load-balancing options, and future generation in Germany and neighbouring countries – in Scenarios 2011 A and C the **load can be covered in all time steps simulated**, and even high peaks of generation from renewables can be utilized in a European grid.

The studies of the electricity supply in a future European grid show that, even with a high share of fluctuating generation, a **large potential for load balancing by transporting electricity** through the transmission network in Europe exists. But even though an analysis of economic cost minimization suggests a consistent strategy of grid expansion, in practice trans-European grid expansion will only be possible to a limited extent, due to local and regional problems of acceptance and political obstacles. For this reason, first a conservative scenario of European grid expansion was derived from an economically optimized supply, using the REMix model **(Figure 10)**. In this scenario, the grid transfer capacity between Germany and neighbouring countries increases by 13.8 GW (high-voltage DC overhead lines) by 2030, and by another 17.6 GW (high-voltage DC underground cables) by 2050.

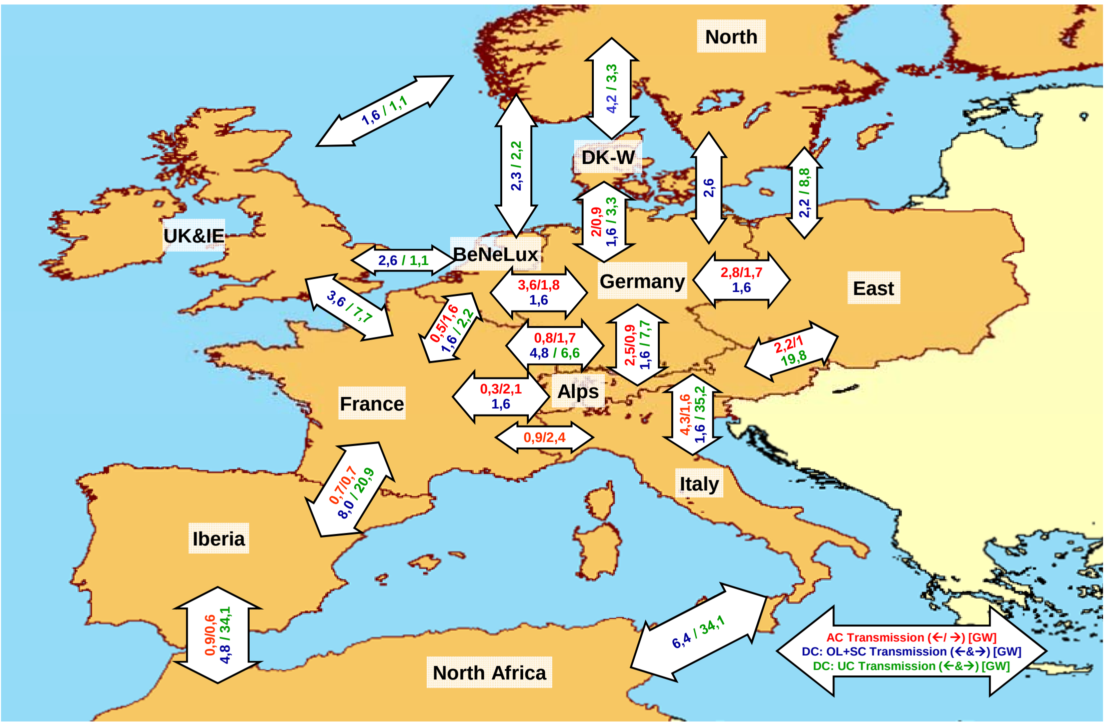


Figure 10: European grid expansion scenario for the year 2050 determined with REMix

AC: high-voltage alternating current; DC: high-voltage direct current; OL: overhead power lines; SC: submarine cables; UC: underground cables

The representation of **load coverage over time** for two episodes selected as typical examples in **Figure 11** shows the fluctuating generation of an electricity supply based to more than 80% on renewable sources of energy in Germany and the neighbouring European regions in the year 2050. There is a clear correlation of the charging of electric vehicles and the production of specified quantities of hydrogen with the generation of electricity from renewables. Of the renewable sources, wind power has the greatest share in the supply; photovoltaics help to cover the load peaks, especially in summer. Concentrating solar-thermal power stations (CSP) (including generating capacity in North Africa) can supply electricity continuously, especially in summer, due to heat-storage systems. The important role of the flexible capacities of gas-fired power stations is also apparent; in 2050, a proportion of hydrogen is already co-fired in them to generate electricity.

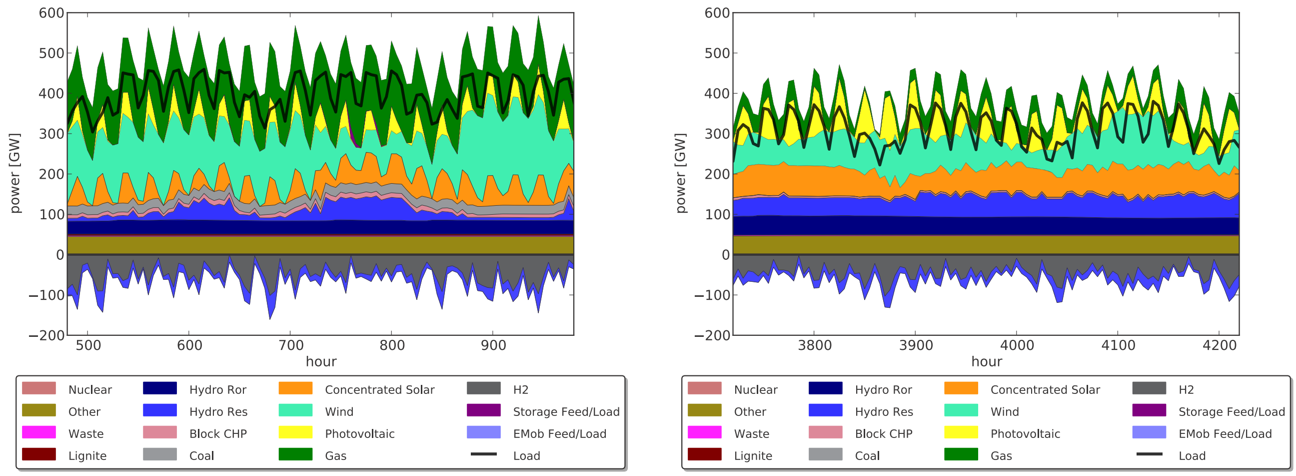


Figure 11: Load coverage over time in Europe for two typical episodes (left, spring – right, summer) for the year 2050 (transportation demand as per Scenario 2011 A). A fixed demand for hydrogen is specified in the simulations

The resulting surpluses of electricity from renewables are very small, since in the expanded transmission grid, and presuming that other load-balancing options are available, **load and generation can always be balanced across Europe** (see load duration curves in **Figure 12**). Due to the grid expansion assumed, and to the balancing potentials of electric vehicles, and the generation of hydrogen to cover a demand profile in transportation, in Scenario 2011 A a relatively small use of pumped storage hydro plants relative to the overall load results. In a comparison between 2030 and 2050, the large increase in generation from renewable sources, and the associated decrease in conventional generation is seen. In 2050, the renewables also contribute significantly to reducing the residual peak loads. The peak generation of fossil-fuel power stations in Europe sinks from about 320 GW to about 190 GW in this period.

The load duration curves for the electricity supply in Germany determined using this approach and these boundary conditions also show the **significant reduction of the peak load by renewables**, as well as the great importance, particularly in 2050, of electricity imports and exports for the electricity supply. Electric vehicles and the generation of hydrogen do raise the load curve, because of the additional demand for electricity; but, depending on the integration of these new consumers (such as controllable recharging of the electric vehicles, demand profiles, local storage capacities for hydrogen, capacity and utilization factor of the electrolysers, etc.), they also have enormous **potentials for load shifting and for utilization of excess power from renewables**. A technically and economically sensible design of these structural options will be the subject of transformation research in the next few years.

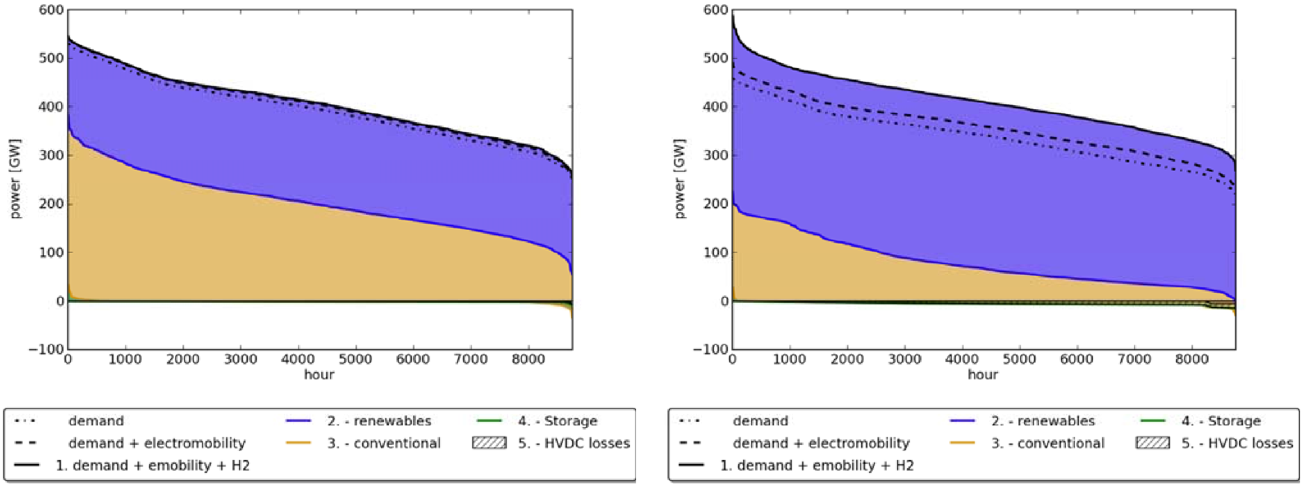
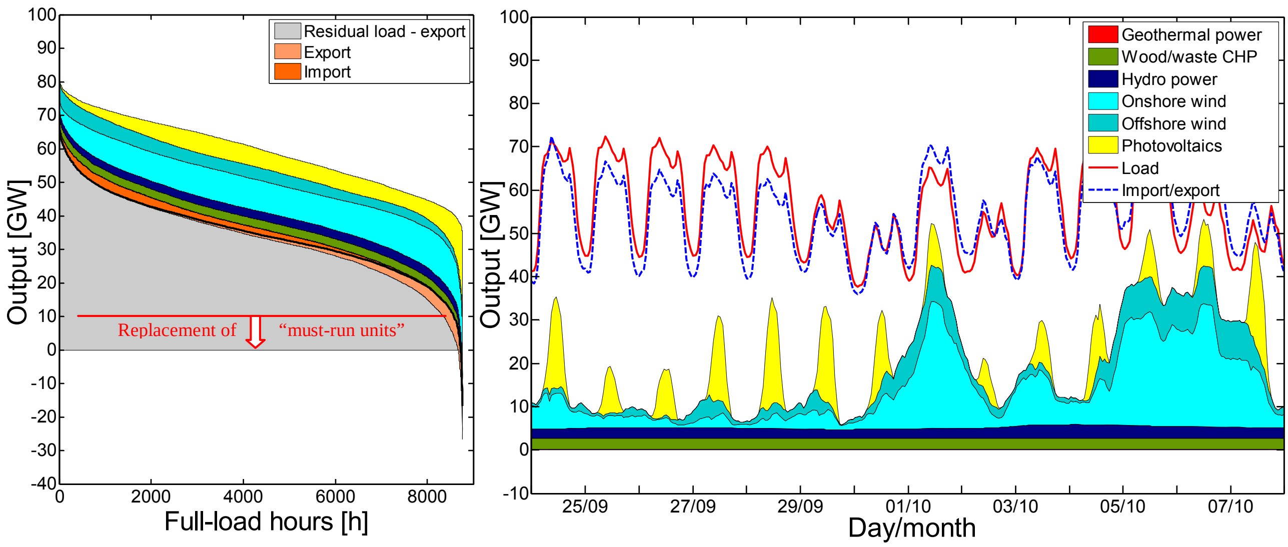


Figure 12: Load duration curves of generation in Europe in the years 2030 (left) and 2050 (right) (transportation demand as per Scenario 2011 A)

Based on the time series for electricity imports and exports between Germany and neighbouring countries modelled with REMix for the European supply system, the flexibility requirements due to volatile feed-in from renewables have been studied in more detail by means of cost-minimized generation scheduling. The studies were performed with rolling scheduling in an hourly chronological resolution. The **influence of forecasting errors** in marginal-cost based generation scheduling, which in reality occurs via the spot markets, was represented by means of the periodic revisions.

The increasing expansion of renewables results in an **increasing demand for operating reserves**, whose size will in future be greatly influenced by the accuracy of forecasts of the feed-in from wind power and solar cells. While the demand for secondary control reserve remains at about the current level, a good 2 GW, until 2030, an increase of the demand for tertiary control reserves to about 7 GW of positive and about 5 GW of negative operating reserve is to be expected. Due to assumed improvements in forecasting, this demand drops again slightly by 2050. By daily tendering, the set of power stations will be able to adjust their provision of operating reserves flexibly to the feed-in from renewables to be expected – therefore this change in market conditions is advisable.

With an ideal expansion of the grid within Germany, hours when the power supply is almost entirely from renewables can already be expected in 2020 (see **Figure 13**). Imports and exports relieve pressure on the system. The fluctuations caused in the electricity system by the volatile feed-in from wind and solar power result in the residual load in a strong **increase in peak-load demand** and a **base-load demand dropping** gradually to zero. Balancing measures are needed to minimize these fluctuations.



a) Load duration curve

b) Typical course of curve over two weeks

Figure 13: Supply-dependent feed-in, electricity consumption, and import-export in 2020, Scenario 2011 A

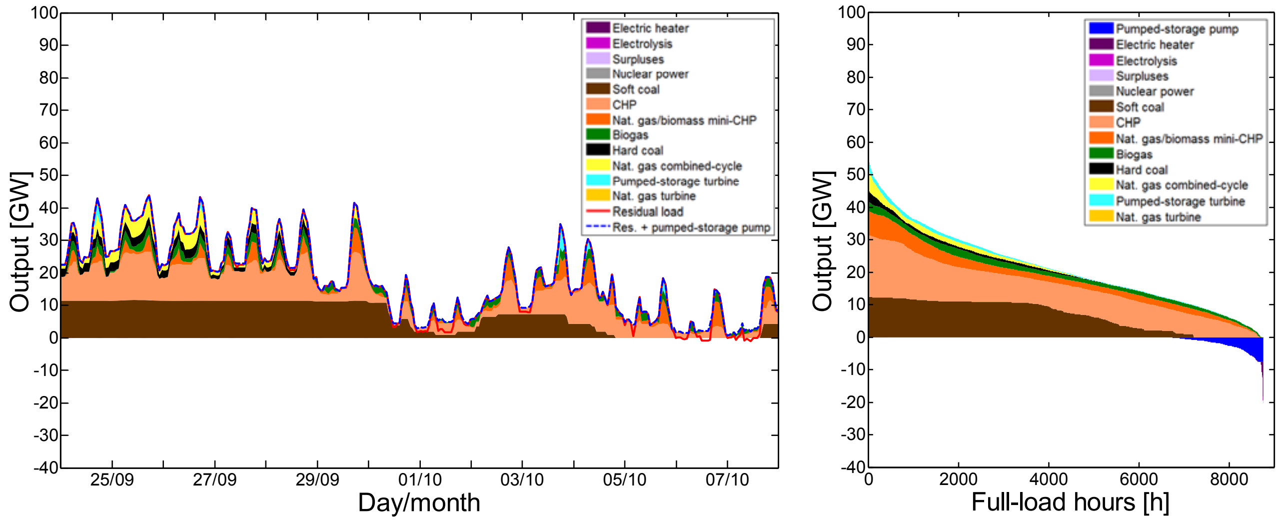
The simulation shows that the wide variety of option can largely even out the residual load. Priority should be given to the **reduction of "must-run units"** and to flexibilization of power stations (CHP, retrofitting), so that they do not block the feed-in from renewables.

The flexibility of the power stations needs to be ensured and rewarded at declining utilization factors. On the one hand, the electricity market must be structured so that a secured capacity is available at all times, while the profitability of all back-up technologies is still guaranteed. On the other, technical requirements for power stations result from this, since only highly flexible power stations will still be able to hold their ground technically and economically. One effective measure would be to incorporate requirements for the flexibility and siting of power stations in the new framework conditions of the electricity market (e.g. **capacity markets**).

This flexibility is also necessary for biomass plants. In periods of surplus wind and solar power, biomass plants must be prevented from supplying power at the same time. An initial instrument has been created for biogas for this with the flexibility premium of the Renewable Energy Sources Act. In the longer term, one should strive for a large **share of biomass in the gas grid**, by means of biomethane, and possibly of wood gas. In this way, the gas infrastructure can be used with gas from renewable sources as a seasonal storage system for flexible compensation of large-scale weather fluctuations, by means of gas-fired power stations and mini-CHP plants that are needed anyway.

How important this flexibility is, is shown by the simulations for the year 2030 **(Figure 14)**. With full flexibility and greatly enlarged electricity grids, the **surpluses from renewables can be integrated almost completely by short-term storage systems**.

Renewable sources of energy can also contribute to **guaranteed capacity**. Due to the seasonal complementarity, the joint capacity credit of wind and photovoltaic power in Scenario A, on the basis of four years' weather, amounts to 7.4 GW (2020), 9.3 GW (2030), and 10.7 GW (2050). There remains accordingly – from a purely national perspective without the European electricity grid – a demand for **guaranteed capacity from thermal power stations** of 68.2 GW (2020), 57.1 GW (2030), and 54.6 GW (2050), which is also reflected in the merit order **(Figure 15)**. Due to the assumed substantial enlargement of CHP capacities and the large savings in electricity consumption, there is only a relatively small need for construction of new condensing power stations. As part of a Europeanization of the energy supply, it is advisable to abandon a purely national perspective on supply security in future. Thus the European grid and the import of controllable power from solar-thermal power stations can in future play a significant role in the guaranteed capacity.



a) Typical course over two weeks

b) Load duration curve

Figure 14: Generation scheduling in Germany in 2030 – Scenario 2011 A

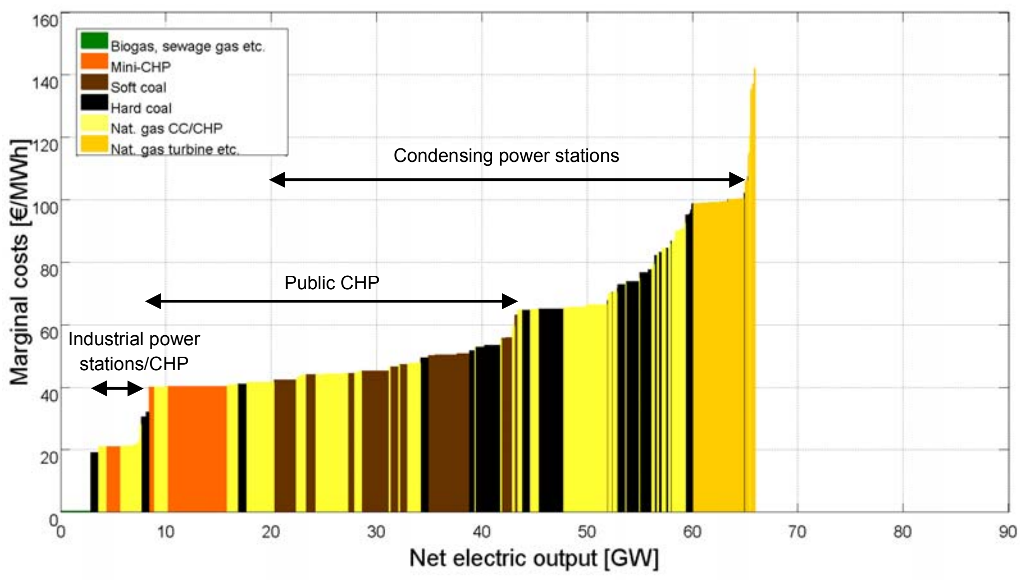


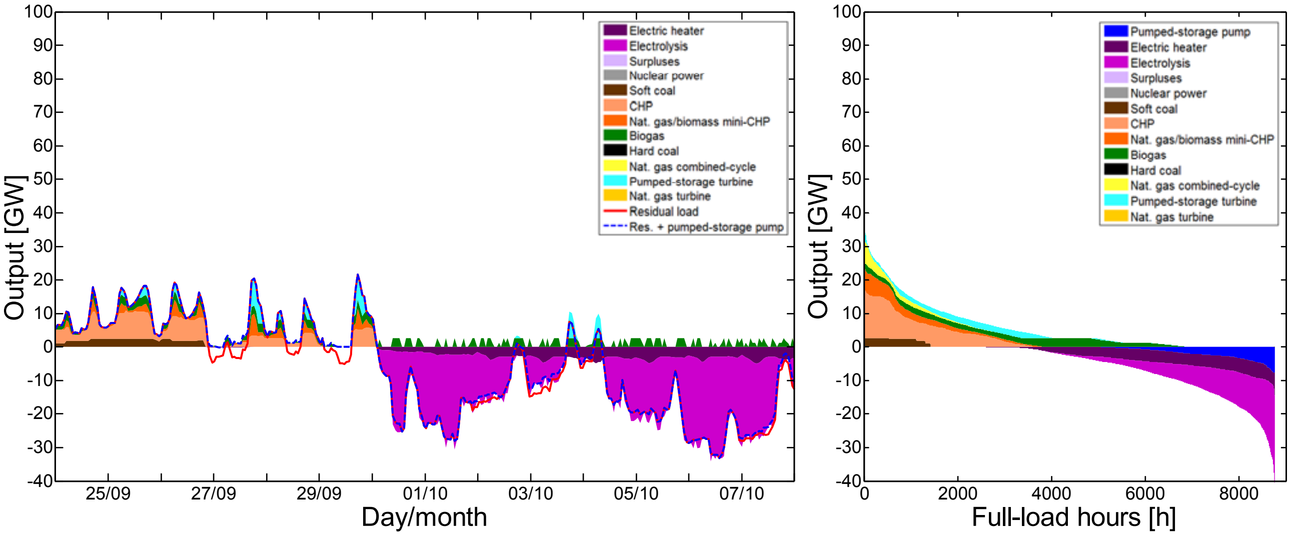
Figure 15: Merit order of thermal power stations in 2030, price path B

The merit order in **Figure 15** illustrates the **importance of CHP** among power stations. The expansion of CHP offers great potentials for efficiency, but should be promoted speedily by 2020, in order to avoid a conflict between the goals of the Energy Concept for expansion of renewables, for rehabilitation of the building stock, and for cogeneration. In the long term, it is foreseeable that, on the one hand, the heat demand for heating will decline, and on the other, the shares of fluctuating renewables will continue to increase. Both factors will make the utilization factor, and thus the profitability, of CHP drop considerably. Therefore, it appears necessary to complete the expansion of CHP by 2020, and to **flexibilize it by means of heat storage systems**, so that the investments are worthwhile and the energy goals are achieved.

Load management can also make a substantial contribution to this. For 2020, a large potential is seen in controlling the existing off-peak storage heaters and electric warm-water storage tanks for tap water. Although these installations should no longer play any role in the heat market in the long term from the environmental point of view, until then, they can make a contribution to integration of the renewables by appropriate control systems. In one or two decades, the potential for load distribution of electromobility, electric heaters, geothermal heat pumps, household appliances, and air conditioning for the benefit of integration of renewables will also develop, showing clearly the advantage of the interaction between the energy sectors electricity, heat, and transportation, and of the overlapping use of energy storage systems (heat storage systems, batteries).

The last option for balancing is the **use of storage systems**, which are needed as both short-term and long-term storage units. **Short-term and long-term storage systems** must be used according to the priority of technical and economic efficiency. Pumped-storage units, and possibly also battery systems, are suitable for hourly and daily balancing; power-to-gas (hydrogen and methane from renewables) or the use of Scandinavian hydroelectric power in perspective for long-term balancing. These energy storage systems can then replace fossil fuels in their storage function. In order to be able to evaluate the long-term potentials of individual storage systems, the demand for storage as a function of the flexibility of the power stations, the speed of expansion of renewables, the expansion of the grid, and the implementation of flexibility measures such as load management must be examined in further research work. Technical and economic questions with regard to the intermittent operation of power-to-gas facilities must also be solved.

The simulation show that until 2030, under ideal conditions, **no significant energy surpluses** (TWh) occur, but almost **only capacity surpluses** (GW); it makes the most economic sense to use these by means of existing and new load-management applications and pumped storage. **Long-term storage systems such as power-to-gas** are only needed in the period after 2030 in this scenario. In **Figure 16**, this can be seen clearly for the year 2050, in which large surpluses for using long-term storage systems exist.

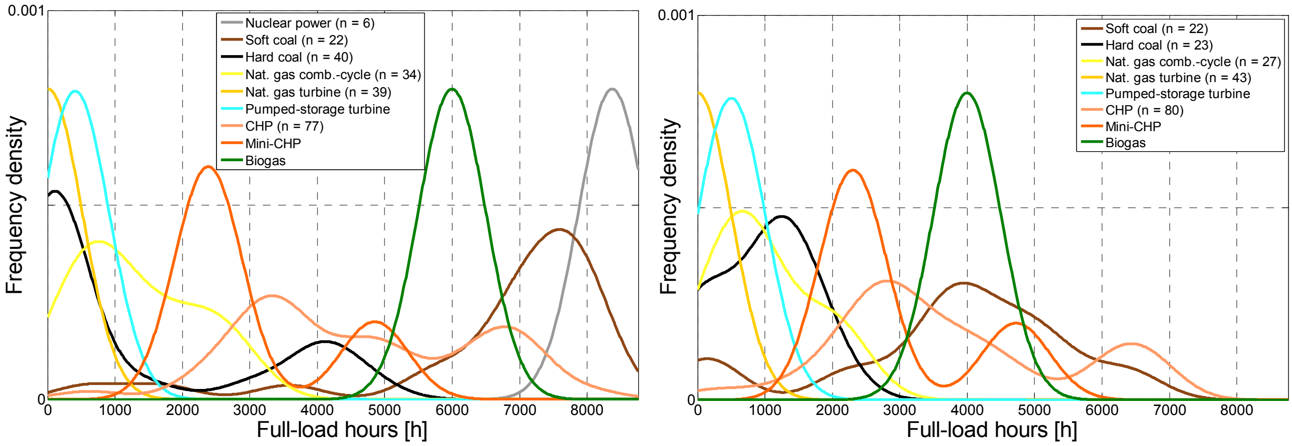


a) Typical course over two weeks

b) load duration curve

Figure 16: Generation scheduling, Scenario 2011 A, in 2050

From the point of view of the national economy, the **most efficient and least expensive flexibility option** should be employed first, in order to implement the most **efficient climate protection** possible. This would include first the adjustment of generation and demand via a corresponding energy management system. The expansion of the grids creates the geographical balance between fluctuating generation from renewables and the demand for electricity, while the storage systems create the balance over time. Overall, by employing the balancing options, limitations on the output from renewables can be avoided, on the one hand, and the power stations can mainly be operated at a **high utilization factor**, on the other – however, with many temporary interruptions and **steep load gradients**. Despite this, the utilization factor of the pure condensing power stations still declines significantly from the present by 2030, as does cogeneration between 2020 and 2050 **(Figure 17)**. Biogas installations will be employed flexibly, with a utilization factor of about 4000 full-load hours, instead of the current base-load input.



a) Scenario 2011 A, in 2020

b) Scenario 2011 A, in 2030

Figure 17: Utilization factor of hydro/thermal power stations – Scenario 2011 A in 2020 and 2030

7 Economic effects of the transformation of the energy supply

The annual installed capacities of the renewables technologies, in conjunction with their unit costs and the assumed economies of scale, determine the **volume of investment** arising from the expansion of renewables. This is an important indicator of the status of the expansion of renewables in the economy. The total volume of investment in renewables amounted **in 2010 to € 27.5 billion per year,** of which 85% went to the electricity sector **(Figure 18)**. The substantial increase in recent years is due to photovoltaics. The investment in this in 2010, at € 19 billion per year, took 70%. In future, the volume of investment in photovoltaic systems will decline significantly, because of further significant economies of scale and more restrictive adjustments to the Renewable Energy Sources Act. For 2020, an installation of 3 GW/yr of capacity and investments of € 3.6 billion per year are assumed. The total volume of investment in renewables in the medium term will be in the range from € 17 to 19 billion annually.

The rapidly growing quantities sold from renewable sources of energy compensate for the further economies of scale occurring in parallel. By 2050, the annual volumes of investment rise to about € 22 billion, thus no longer reaching the peak values of the years 2010 and 2011, which have been mainly caused by the photovoltaic installations. These stable volumes of investment in the coming decades are an essential precondition for German firms to play a strong role in the world market in the majority of renewables technologies, thus enabling the establishment of export markets to continue. This confirms emphatically the necessity of the Energy Concept's goals for expansion of renewables of 18% for 2020 and 60% for 2050.

By the end of 2010, a total of around € 150 billion had been invested in renewables installations to generate electricity and heat. In the coming decades until 2050, the level of investments in renewables is **about € 200 billion per decade**. The investments rise considerably higher, up to € 250 billion per decade (2030-2040) to € 350 billion (2040-2050), if the pre-eminent climate-protection goal (95% less greenhouse-gas emissions) is to be achieved by 2060. The further global growth of the renewables is also the precondition for achieving further cost reductions for most renewables technologies. The **average electricity production costs** of all installed new facilities were **about 14 ct/kWh$_{el}$ in 2010**. They have increased significantly in recent years because of the large expansion of photovoltaic systems. But the maximum has now been reached, and by 2020, the mean value of the total mix already drops significantly to 9.2 ct$_{2009}$/kWh$_{el}$ and further by 2050 to 6.4 ct$_{2009}$/kWh$_{el}$. For all technologies for generating electricity from renewable sources of energy, **in the longer term, production costs ranging from 5 to 9 ct$_{2009}$/kWh$_{el}$** are established. Of major importance for an economic comparison with conventional technologies is that the cost trends for renewables, compared to a fuel-based energy supply, can be calculated considerably better in the long term, since they are mainly affected by technological developments, and less by the trends in fuel prices. Furthermore, renewable sources of energy increasingly represent a growth segment of the economy that meets essential sustainability criteria. So they can in future **replace environmentally harmful and resource-exhausting fields of growth.**

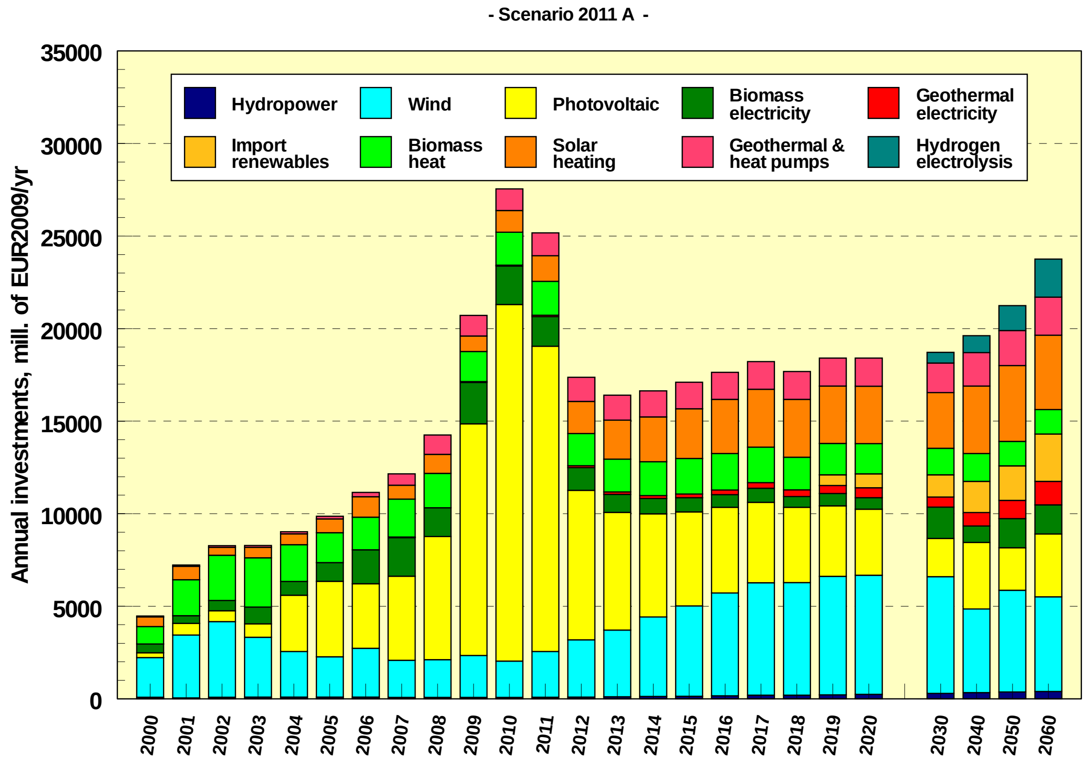


Figure 18: Annual volume of investment in Scenario 2011 A for electricity and heat generating renewables technologies

In fossil-fuel power stations coming on line in 2020, the electricity generating costs will already lie between **6.0 and 7.7 ct$_{2009}$/kWh$_{el}$** (price path A, utilization factor 6000 h/yr, **Table 6**); by 2030 they will increase to **7.2-9.4 ct$_{2009}$/kWh$_{el}$**. Then the generating costs for electricity from renewables, at 7.6 ct$_{2009}$/kWh$_{el}$ (mean value for all new plants) will already be lower than for electricity from new hard-coal-fired and gas-fired power stations. If the external costs of climate change (characterized here with a cost value of € 75 per ton of CO_2), which have not been internalized to date, were taken into account in the costing, then the environmentally **"correct" price level** would already be about **10 ct_{2009}/kWh_{el}** today. The large discrepancy from the costs actually calculated in business economics today shows that these price signals, which are incorrect from the environmental point of view, must be corrected rapidly and substantially, if an energy system that is acceptable from the point of view of the climate is to created and maintained under the regime of "correct market prices".

Table 6: Prices of CO_2 allowances ($€_{2009}/t$) and generating costs (ct_{2009}/kWh_{th}) of new fossil-fuel power stations at a utilization factor of 6000 h/yr (annual interest 6%; amortization over 25 years) for different price paths

	2010	2020	2030	2040	2050
Price path A					
CO_2 price	14.3	27	45	60	75
Natural gas	5.9	7.6	9.4	11.3	13.1
Hard coal	5.7	7.7	9.8	11.7	13.6
Lignite	5.0	6.0	7.3	8.6	10.0
Price path B					
CO_2 price	14.3	23	34	45	57
Natural gas	5.9	6.8	7.6	9.0	10.1
Hard coal	5.7	6.8	8.0	9.3	10.6
Lignite	5.0	5.6	6.4	7.3	8.4
Price path A, plus full internalization of climate-protection costs (€ 75 /t CO_2) from 2010 on					
CO_2 price	75	75	75	75	75
Natural gas	8.0	9.2	10.4	11.8	13.1
Hard coal	10.1	10.9	11.7	12.7	13.6
Lignite	10.7	10.1	9.8	9.9	10.0
Price path as per scenarios for Energy Concept [EWI 2010]					
CO_2 price	14.3	20	38	57	75
Natural gas	4.9	5.0	5.8	6.7	7.6
Hard coal	5.0	5.3	6.5	7.7	8.8
Lignite	4.8	5.5	6.7	8.0	9.3

The **costs of introducing renewables** are represented in this study by means of **"system-analytical differential costs"** with respect to a fictitious energy supply system that covers its demand for energy without renewable sources of energy. These are based on the production costs of the expansion of renewables in the electricity, heat, and transportation sectors, compared to fossil-fuel and nuclear alternatives, and can be illustrated by annuity investment costs (capital costs) plus fuel costs for biomass and fossil-fuel demand, and plus other operating costs (and credits, where applicable), compared to the full costs of fossil-fuel energy facilities (cf. Table 6). In one price variant, the external costs of damage from climate change are taken into account approximately in determining the differential costs, as well.

The differential costs determined here do not include the additional expenditures for incorporating the fluctuating supply from renewables into the overall electricity supply system. If a complete network model for an energy system based largely on renewables were available, the **"differential costs" of grid expansion** in comparison to grid expenditures for a conventional energy supply could also be determined. An estimate shows that, taking into account the additional grid expansion, the differential costs calculated would be about 12-13% higher. This would not make any fundamental difference to the following statements on the economic viability of expansion of renewables. The differential costs shown here must not be confused with the "Renewable Energy Sources Act differential costs".The latter describe the additional costs arising from the application of the Renewable Energy Sources Act, compared to prices on the electricity spot market. These are passed on and paid by the non-exempted electricity customers as part of their electricity bill in the form of the EEG surcharge ("EEG-Umlage").

Summed up over all sectors, the **system-analytical differential costs** for the entire expansion of renewables amount **in the year 2010 to € 12.4 billion annually**. Of this, 75% is due to electricity generation from renewables. The reason for this is the relatively high differential costs of photovoltaic systems. The differential costs of other electricity generation, at about € 4 billion per year, are of the same order of magnitude as those of heat generation from renewables. The total differential costs rise to a maximum of € 15.5 billion per year in 2015 (price path A), of which € 12 billion per year are for the electricity sector, € 2.4 billion per year for the heat sector, and € 1.1 billion per year for the fuel sector. **In about 2026, there are already no differential costs any more** for the overall expansion of renewables. At that time, the renewables already cover a good 30% of the total final-energy consumption. The negative differential costs occurring after that – which already come to minus € 7 billion in 2030 – mean that after that time, the renewables stabilize the level of energy costs to the consumer, or even decrease them, compared to a fossil-fuel supply.

By 2010, about € 71 billion of system-analytical differential costs had arisen for the overall expansion of renewables, if compared to the electricity costs or heat and fuel prices previously applicable **(Figure 19)**. Of this, € 44 billion came from the electricity supply, € 23 billion were caused by heat supply from renewables, and € 4 billion from provision of biofuels. If one adds to this the following decade blocks, the **cumulative differential costs by 2020 increase to € 210 billion**, and by 2030 to only slightly more, € 219 billion (price path A). Of this, expansion of electricity from renewables accounts for € 181 billion (which is 76%), and provision of heat from renewables for € 34 billion.

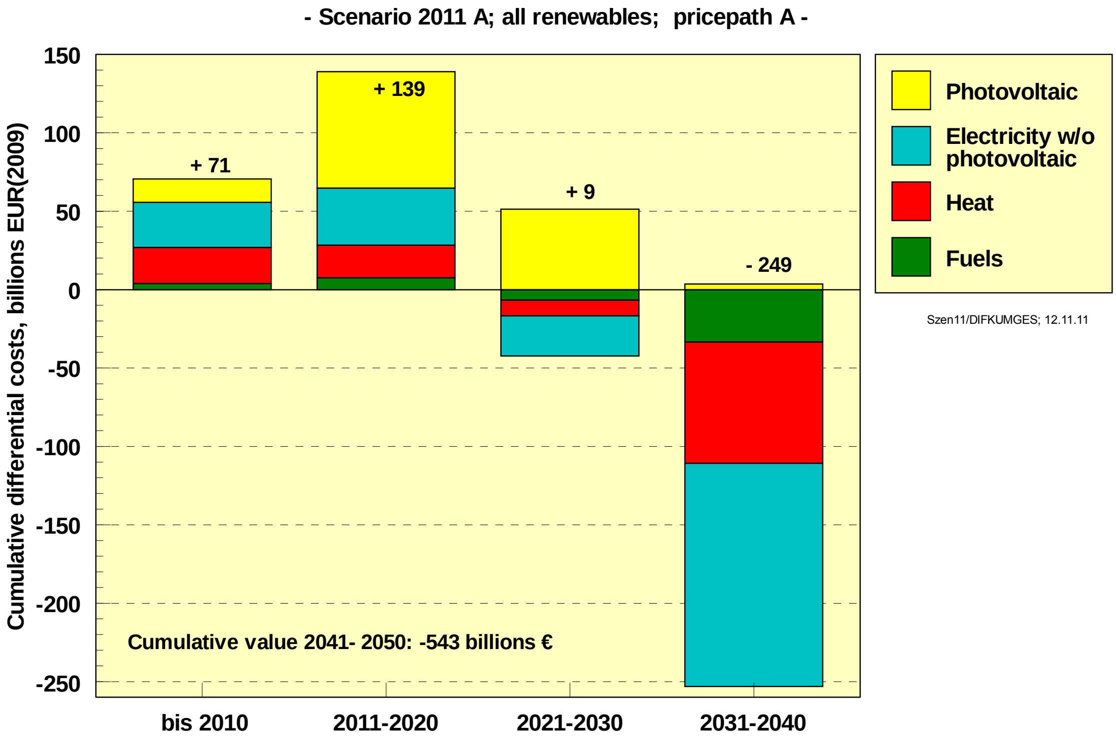


Figure 19: Cumulative system-analytical differential costs of entire provision of energy from renewables in Scenario 2011 A for 10-year segments and price path A

At the end of 2040, the cumulative system-analytical differential costs of all renewables technologies have been completely compensated, with a balance of minus € 30 billion. At mid-century, the supply from renewables (final-energy share in 2050: 70%) has already **prevented potential additional expenses of about € 570 billion** compared to a (fictitious) continuation of an energy supply from fossil fuels.

If prices rise according to Path B **(Table 7)**, the compensation does not occur until shortly before 2050 (balance minus € 42 billion). For a very low price rise according to Path C, the cumulative differential costs would increase until 2040. By contrast, taking into account external costs in the form of potential climate damage at € 75/t CO_2 shows that the entire expansion of renewables can in principle be achieved at very low differential costs. By 2020, maximum cumulative differential costs amounting to € 52 billion occur. Shortly after 2020, the avoided costs of climate damage already outweigh the costs that would occur if the fossil-fuel energy supply was continued. The results show that assumptions about the future price trends of fossil fuels and about the cost level of CO_2 allowances influence the economic evaluation of the expansion of renewables very strongly. Thus plausible assumptions are of great importance for a correct energy-policy evaluation of the expansion of renewables.

Table 7: Cumulative system-analytical differential costs of entire expansion of renewables as per Scenario 2011 A for four paths of applicable energy prices (€$_{2009}$ billions)

Price paths	Path A ("Substantial")	Path B ("Moderate")	Path C ("Very low")	Costs internalized
until 2010	71	71	71	16
until 2020	210	230	245	52
until 2030	219	324	395	-38
until 2040	-30	250	416	-352
until 2050	-573	-42	279	-918

The mean generating costs for electricity from renewables (blue curve in **Figure 20**) are currently well over those of conventional producers. In 2010, this caused an increase of the mean generating costs for the entire electricity supply by 1.7 ct/kWh to 6.5 ct/kWh. The **value rises further to 2.3 ct/kWh in 2016**, resulting in mean generating costs of 8.4 ct/kWh in total. After this, the generating costs from renewables, which continue to sink due to further technical innovations and continuous expansion of the market, permit a reduction in mean generating costs for the entire electricity supply to a level of **barely 7 ct/kWh in 2050**. Thus the cost level in 2050 (in real 2009 prices) is only slightly higher than today. But in contrast to today, electricity is then available from low-risk, largely climate-neutral sources of energy available in unlimited amounts.

At the moment, in 2012 the levy for renewables based on the system-analytical differential costs (which relates to the total net generation) of **2.09 ct$_{2009}$/kWh in the year 2012** contrasts with an official EEG surcharge of 3.59 ct$_{2012}$/kWh. This substantial difference makes it clear that the levy defined from the specific point of view of the Renewable Energy Sources Act's specifications cannot evaluate the macroeconomic effect of a comprehensive transformation to renewables appropriately.

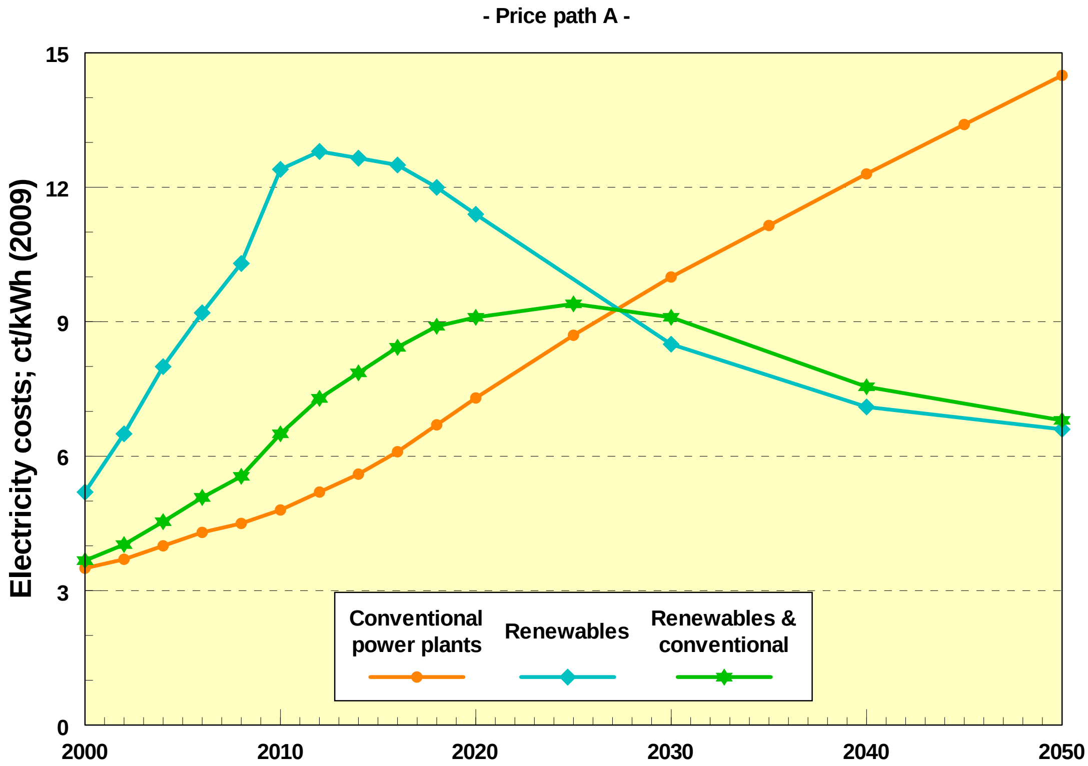


Figure 20: Mean generating costs of conventional power plants, of the renewables mix, and of the entirety of all generating facilities in Scenario 2011 A for energy-price development as per price path A

The facts as stated above for the electricity sector can be presented approximately for the entire energy supply system, as well. The energy consumers currently spend in total about **€$_{2009}$ 200 billion annually** on heating fuels (ca. € 70 billion), motor fuels (ca. € 45 billion) and electricity (ca. € 85 billion) **(Figure 21)**. In 2005, it was still only about € 160 billion. If the present rate of energy consumption were frozen, and covered entirely from fossil fuels in future, in price path A, about €$_{2009}$ 320 billion annually would need to be spent for this in 2030, and in 2050 about €$_{2009}$ 415 billion annually (grey line: “Fossil-fuel without efficiency”). A consistent strategy of **substantial increases in efficient and simultaneous expansion of renewables allows uncoupling** from this unsustainable trend. If only the efficiency strategy is considered, the expenditures for the future energy supply can be kept just under €$_{2009}$ 300 billion per year (green line: “fossil-fuel with efficiency”). The specific cost level (per kilowatt-hour) until 2050 would then be 2.2 times higher, but the “energy bill” would only increase by 50% over 2010. In combination with the expansion of renewables (red line: “Scenario 2011 A, efficiency & renewables”), a complete **transition to a sustainable energy supply system** is achieved. Until about 2025, the differential costs of expansion of renewables for electricity, heat, and fuels are additional expenditures, so that the total expenditures on energy (excluding costs for the integration of the fluctuating supply of electricity from renewables into the supply system) rise to €$_{2009}$ 285 billion annually by 2025. After that, they decline to the extent to which the efficiency-plus-renewables strategy takes effect. In 2050, with total expenditures amounting to €$_{2009}$ 215 billion annually, roughly the **current level of expenditure is reached again**, although the energy-price level of energies from fossil fuels is more than twice as high as at present.

Thus an effective efficiency-plus-renewables strategy designed for the long term enables both a climate-compatible and low-risk energy supply system to be created, and the costs for this to be kept stable after a transition period. Therefore, the main task should be to convey to the citizenry and the economic players that the inputs now necessary for this transformation, in the form of investments in efficiency and renewable technologies and the infrastructures to be adapted correspondingly, or the resultant servicing of capital, are **necessary and sensible provisions** for creating a sustainable energy supply system.

The change of role of renewables, from a niche to a leading position, which is desired in energy policy, can be understood as a **"forced" internalization of external costs** of the existing conventional energy generation. The capital costs of the renewables also represent almost completely the "ecological" full costs of the respective generation of energy from renewable sources. Costs that can be displaced to a later date or into other regions (and can thus be suppressed) exist only to a very small extent. They occur, for example, from the competing uses of biomass or in the local influences on the landscape from the erection of renewables installations. If the corresponding willingness to engage in dialogue is present, they can usually be solved at that level, too.

By contrast, large parts of the costs in conventional generation are still not included in business costing, in particular the damage from global climate change. The resultant costs of environmental pollution or destruction by the ever more complex winning of fossil fuels are also almost entirely lacking in the cost calculations. And fundamental risks, such as are inherently associated with the use of nuclear power, are not taken into account, either.

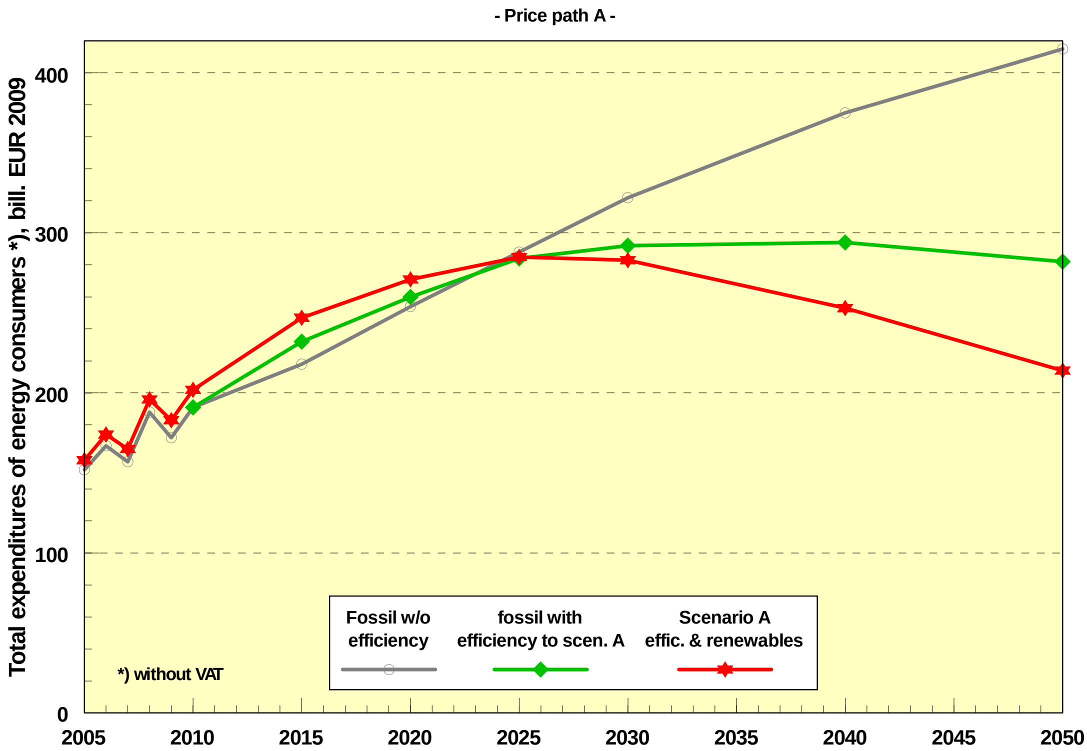


Figure 21: Total expenditures on energy of all consumers for provision of the present consumption level entirely from fossil fuels, if the efficiency goals are implements, and for the energy mix of Scenario 2011 A

In 2010, Germany imported fossil energy carriers (about 10,100 PJ/yr) worth € 68 billion. Sparing fossil resources by increased use of energy from renewable sources leads to a **considerable reduction in imports of fossil fuels**. At present, they have an avoidance effect of 1,100 PJ/yr of imports of energy from fossil fuels. In this way, $€_{2009}$/ 6.8 billion annually of expenditures on imports were avoided in 2010. The amount of imports avoided grows to about 4,100 PJ/yr by mid-century. In this way, expenditures on imports of $€_{2009}$ 17 to 20 billion per year are avoided in 2020, and €$_{2009}$ 30 to 36 billion per year in 2030. By mid-century, the expenditures on imports for fossil fuels avoided annually will have risen to €$_{2009}$ 54 to 73 billion, which equals about 2% of the gross domestic product expected then. The CO_2 emissions avoided by the use of renewables also reach considerable values in the future. In 2010, about 115 million metric tons of CO_2 were avoided through renewables. This represents a value of € 1.6 billion per year (CO_2 price € 14.3/t), but in fact, climate damage amounting to about € 8.5 billion per year (CO_2 price € 75/t) was avoided. For a quantity of carbon dioxide avoided in 2050 by the use of renewables of 396 million t CO_2/yr, this corresponds to global climate damage avoided by Germany of about € 32 billion per year.

Various studies show the **problems of drawing up a balance sheet of the benefits of renewable energies**. For one thing, a number of positive effects of an expansion of renewables are not or hardly quantifiable. These include the reduction or avoidance of international tensions due to less competition for scarce fossil fuels, the non-existing or hardly existing potential for misuse of renewables technologies for military or terrorist purposes, and thus a less problematic transnational cooperation, or the numerous possibilities for decentralized usage of renewables technologies, with added value in local regions and the increased possibilities for participation and decision-making by private persons and local government. For another, the quantifiable amounts of benefits are largely theoretical as yet, since they are mostly not included in the cost calculations by market participants, and thus investment decisions are not “automatically” made according to the optimum economic benefit.

At present, the necessary corrections in the form of support instruments and other government “guard-rails” are perceived as cost factors, and thus **mainly negatively as “burdens”**. But the corrections of this “market failure”, which in the final result involve “price increases”, must be seen by a courageous and **enlightened energy and climate-protection policy**, which gives equal priority to environmental and climate-protection concerns with the interests of economic and social policy, as necessary measures that are useful in the long term, and this view must be conveyed to the citizenry. Otherwise, the transformation process to an energy supply based on renewable sources and high energy efficiency, as announced in the Federal government’s Energy Concept, will not materialize.

8 Security-related aspects of the transformation of the energy supply system

The expansion of renewable sources of energy has a determining influence on the security and reliability of the future energy supply. Not only technical and structural, economic, and social aspects, but also aspects of development-aid policy play a role in this. Various security aspects of energy services are subsumed under the concept “energy security”. These are: **reliability of supply, internal security, investment and economic security, environmental and climate safety, and international security.**

All in all, transformation to an energy system for electricity and heat supply and transportation based on renewables shows a number of features that suggest an **increase in “energy security”** overall. These positive security-related features of such a transformation are:

- predominant share of domestic sources of energy, reduced dependence on imports;
- less structural vulnerability, due to predominantly decentralized generation;
- generation more compatible with the environment and climate; avoidance of the risks of nuclear power;

- larger variety of the sources of energy used, generation on a considerably larger geographical area, larger number of supply corridors;
- sinking prices of technology, and thus of energy, if expansion of renewables is pushed;
- high cost stability and labour intensity, due to dominance of the capital costs;
- prolongation of the availability of well storable fossil fuels;
- international cooperation and conflict prevention, considerable opportunities for developing and newly industrializing countries, in particular the potential EUMENA Energy Community.

Security-related features that present an **energy-policy challenge**, and which must be dealt with in the transformation process, or which might make an increase in “energy security” more difficult, are:

A) ensuring the reliability of supply on the basis of mainly fluctuating sources of energy requires a large expansion of infrastructure measures such as grid transfer capacity, energy storage systems, and load and generation management;

B) high investment costs at the beginning of the development of the technology, and corresponding economic “provisions in advance”;

C) creating a suitable or modified market-economy framework for mobilizing a sufficiently large number of players;

D) the predominant energy carriers in an energy system based on renewables, electricity and gas, have to run through lines, and are more vulnerable;

E) problems of acceptance in some localities for renewables installations and corresponding infrastructure measures, particularly if these are very visible.

A transformation of the German and European energy supply system can take its bearings from the following pointers, in order to **keep “energy security” as stable as possible, or increase it**:

A) Accompanying the expansion of fluctuating renewable sources of energy by sufficient building of flexible conventional power stations, fuelled only by natural gas, supplemented by biogases and, in the longer term, gases from renewable sources. In parallel, decommissioning of conventional power stations with little scope for regulating (“must-run units”);

B) Expansion of renewable sources of energy that are reliably available, such as generation from biomass within the scope of its permissible “ecological” potential, and geothermal generation;

C) Increasing the Europe-wide transfer capacity of the electricity grid for improved large-area balancing of the fluctuating supply from renewable sources of energy and the demand for energy;

D) Increasing the storage capacity in the German and European grid by means of pumped-storage power stations, compressed-air storage systems, and, in the long term, hydrogen or methane from renewables, to improve the indirect regulation of fluctuating renewable sources;

E) Load management for adjusting the load to the fluctuating supply from renewables, by developing smart consumers appliances and grids, while making use of synergies in coupling the electricity sector to the heat and transportation sectors;

F) Converting heat-controlled to electricity-controlled cogeneration with the help of heat-storage systems, and further expansion of electricity-controlled cogeneration;

G) Importing reliably available renewables electricity from solar-thermal power stations in North Africa (DESERTEC) and hydro-electric power from Scandinavia;

H) Enabling the use of electricity from renewables for the transportation and heat sectors by intelligent direct use and by conversion into synthetic storable fuels, such as hydrogen or methane from renewables.

And finally, what is indispensable for achieving the maximum possible social approval and acceptance for the objectives of the transformation process is an **energy policy with great transparency, reliability, predictability, and purposefulness**, so that the necessary instruments and measures can be refined or established in time with the necessary political and social majorities.

9 Conclusions and recommendations

The importance of the elements of the strategy "increased efficiency" (EFF) and "use of renewable sources of energy" (RES) vary greatly in the sectors electricity, heat, and transportation. In the field of the power supply, CO_2 reduction by the use of renewables clearly dominates, with a net reduction of 209 million t CO_2/yr. The contribution from efficiency measures in electricity consumption is relatively small, at 51 million t CO_2/yr, because gross electricity generation decreases only slightly until 2050. By contrast, the CO_2 reduction in the provision of heat is achieved mainly by the substantial reduction of heat consumption. Efficiency measures account for 196 million t CO_2/yr, expansion of renewables for 47 million t CO_2/yr. There is a similar weighting with motor fuels, where a reduction of 96 million t CO_2/yr is due to efficiency measures, and of 26 million t CO_2/yr to the use of renewables. However, it should be noted that the reduced consumption of final energy in the transportation sector due to the introduction of electromobility is accounted for under "efficiency". Electromobility using electricity from renewables alone makes a contribution to reduction of about 23 million t CO_2/yr in Scenarios A and B, and 42 million t CO_2/yr in Scenario C.

The successful implementation of the CO_2 reductions to be achieved requires in each field the combination of substantial structural changes, the **employment of a wide variety of sets of energy-policy measures with targeted incentives** for numerous individual actors, as well as overcoming numerous obstacles and particular interests. In addition, the **interactions between the fields** grow, due to growing balancing and storage processes, both between the supply of electricity and heat, and between the supply of electricity and gas. Therefore, the course over time of the change processes must be carefully matched to one another.

In the Energy Concept, **halving the total energy consumption** in Germany is specified as a goal. However, at present, a **wider and wider gap** is opening between the Federal government's appropriate goals for energy efficiency and the actual effects of the current instruments. This must be closed rapidly by much more effective instruments and measures. Without an augmented energy-efficiency policy going well beyond the efforts to date, the Energy Concept's ambitious goals for climate and resource protection cannot be achieved.

The recommended measures for implementing the objectives of the Energy Concept are explained in detail in the full-length version of this study (in German). They are outlined briefly here:

1. Efficiency increases in the electricity sector

A) Establishment of an **Energy Efficiency Fund** financed from the "*Energie- und Klimafonds*" government Special Fund.

B) Expansion of a clear labelling requirement for electrical equipment in the context of the **EU's Eco-Design Directive**.

C) Full support for the draft of a **European Energy-Efficiency Directive**; improvement of the Directive for more ambitious efficiency goals.

D) The future **use of electricity in the heat sector** must be largely coupled to surpluses of electricity from renewables; electric storage heating should only be used in buildings with high insulation standards; the use of electric direct heaters to provide space heat and hot water should be curtailed substantially.

E) **Regulatory specifications** should be developed for company and local-authority energy-usage conceptual plans, and for augmenting of savings-directed power contracting schemes.

F) Re-orientation of the **Energy and Electricity Tax Act** (*Energie- und Stromsteuergesetz*), or of the environment tax, towards additional economic incentives for increasing efficiency.

G) **Reviewing tax privileges** and exemptions in industry; linking them to proof of efficient energy-management systems.

2. Efficiency increases in the heat sector

A) **Tightening the Energy Saving Ordinance** (*EnEV*) for new building to the standard of a "climate-neutral building" by the year 2020, in combination with higher shares of renewables in the Renewable Energies Heat Act (*EEWärmeG*).

B) Drawing up a "**renovation timetable for the existing building stock**" in the context of an amended Energy Saving Ordinance (*EnEV*), stepping up the rate of renovation, ensuring sufficiently thoroughgoing renovation with respect to energy, and ensuring sufficient funds are available for the support instruments.

C) Improved possibilities of **energy contracting for rental housing;** amendment of rent laws to make the amortization of investments in efficiency measures easier.

D) Passing and implementing **tax deductions** for the costs of energy-oriented renovation of buildings.

E) Supervision of the implementation and accompanying **monitoring** of the "Modernization Offensive".

F) Obligation to develop and support municipal or town-quarter-oriented, coordinated **renovation and heating conceptual plans**, with a view to **local district heating** from CHP or renewable sources of energy, tailored to the need ("Climate Protection Acts").

G) Increased incentives or subsidy programmes for **energy-management systems** and the energy optimization of energy-intensive processes; support instruments for innovative technologies to increase energy efficiency in industry.

H) Obligation to **use waste heat** for cascade processes; augmented energy contracting in the process-heat field.

3. Transformation of the electricity supply

A) The **Renewable Energy Sources Act (*EEG*)** is the most effective instrument for promoting the expansion of renewables in the electricity sector. The fundamental principle of **priority for renewable sources of energy** must be maintained basically unchanged; its **continuous refinement and adaptation** to technological innovations that reduce costs must be preserved in principle, but it should be structured more flexibly.

B) The current **exemptions from the EEG surcharge ("*EEG-Umlage"*)** should be reviewed, and curtailed as much as possible. Whether the Market Premium makes sense should also be reconsidered if it does not lead to a significant improvement in market integration of RES.

C) **The flexibility** of the remaining conventional power stations must be increased considerably; in future, only very flexible power stations will be technically and economically viable.

D) **Renewables facilities must also assume responsibility for the system;** in future, they must also contribute to grid reliability (controlling power range for maintaining frequency and voltage; protective relaying, et al.)

E) The grid must be expanded more rapidly, both at the **distribution level** and on the **transmission level**; the electricity-supply scenarios currently presented by the Federal Network Agency (*Bundesnetzagentur*), now that they have been revised, provide a suitable framework for drawing up the necessary **grid development plan**.

F) Increased incentives for the further **expansion of cogeneration** are needed, primarily with heat storage systems; biomass CHP plants only with an obligation to utilize the heat.

G) The **"optimum" structure of the future storage demand** should be determined as precisely as possible in further studies, varying the essential parameters, such as flexibility of the power stations, degree of expansion of renewables and of the grid, as well as the flexibility of load-management measures; further research work is required on the technical refinement of storage systems.

H) The **profitability of the necessary back-up technologies must be ensured**; adjusted structural conditions of the electricity market should also incorporate requirements for the flexibility and location of the power stations, and reward these (e.g. by means of "capacity markets").

I) It is necessary to integrate the **full costs of all generating options** into the price signals of the future electricity market to a growing extent. The goal should be that the full costs largely contain the external costs of providing energy (especially the costs of climate change and the costs of waste disposal and of risks).

4. Expansion of renewables in the heat sector

A) A comprehensive re-organization of the Market Incentive Programme (*MAP*) should be carried out, with the objective of overcoming the present budget restrictions. **A non-budgetary subsidy instrument**, such as the EEG is in the electricity market, should be introduced. This must include the existing stock of older buildings in particular.

B) Local authorities should be obligated to draw up uniformly structured, **comprehensive heat plans or energy conceptual plans**; the possible contribution of local district-heating supplies based on solar and geothermal heat should be given particular attention.

C) For larger **solar-collector systems, further development to lower costs is needed;** in the **exploitation of deep geothermal heat,** more attention should be paid to the provision and distribution of heat.

D) Further development of inexpensive **long-term thermal storage systems** should be pushed, as should studies and pilot projects on the integration of heat storage, heat pumps, and district heating schemes into electricity load management.

E) Expansion of the incentives for **renewables-based heating networks**, and the conversion of existing heating networks to supply from renewables.

5. Development strategies in the transportation sector

A) Incentives and specifications (in particular, the consistent tightening of the CO_2 limit values for fleets of new vehicles) should be set for the further substantial **reduction of specific fuels consumptions** of motor cars (50-60%) and utility vehicles (>30%).

B) The incentives for **enlargement of the market for lighter and also smaller motor vehicles** should be augmented, for example by introducing a general speed limit, abolishing the tax privileges for company cars, and modifying the flat-rate tax deduction for commuters.

C) A substantial **shifting of goods traffic to railways** by increasing and shifting investment funds for the necessary railway lines is essential.

D) An **integrated mobility concept** should be drawn up, which studies the development of traffic based on social, demographic, and structural factors, includes all transport operators, and has the goal of the greatest possible flexibility and interoperability of all transport operators.

E) For a general replacement of fossil motor fuels, **all options for renewables-based motor fuels** are needed; **biofuels** have clear limits to their potential; they must be developed further with respect to the achievable yield and the employable biomasses; the climate effectiveness of biofuels must be studied more comprehensively.

F) The largest possible contributions from electricity from renewables and electric vehicles should be sought. For this, the **further development of electric vehicles** and of the public battery-charging infrastructure, taking the technical requirements of the grid into account, is needed.

G) A **conceptual plan for bringing electric vehicles onto the market** via greater tax incentives or the like, to compensate for the extra costs, should be drawn up.

H) **Chemical fuels derived from renewables** (hydrogen or methane) have an almost unlimited potential, but their use in transportation requires further development, and innovations that lower costs and optimization studies of the necessary infrastructures.

The evaluation of the transformation strategy in the energy sector requires a **view extending beyond the periods** which are normally considered in day-to-day politics, by business, and especially by the financial markets when making decisions. With the Energy Concept, our politicians have shown that they are in principle able and willing to include the necessary longer-term development periods in their decisions. This promising approach should be maintained and refined, and find expression in the instruments and measures that are necessary for the transformation process. This includes, in particular, informing the citizenry of the **environmental usefulness and economic expediency** of the strategy adopted more than has been done so far.

In order to keep “rebound effects” (additional energy consumption induced by efficiency gains) as small as possible, it will also be necessary to initiate an **intensified dialogue in society** on other models of prosperity and on sustainable consumer behaviour, and to point out the interactions with climate and resource protection. This dialogue must also include how the existing **“ecological” market failure** – i.e. the insufficient price signals of the present energy market concerning climate protection and reduction of other environmental pollution – can be corrected.

The unambiguous findings on climate change and its consequences, the economic risks of an energy supply largely dependent on imports of fossil fuels, the awareness of the growing environmental hazards of the ever more complicated winning of further fossil raw materials for fuel, and the still unsolved questions of safe disposal of nuclear fuels, should make it easier to win over more and more social and business actors to the **necessary transformation process** of the energy supply system towards substantial increases in efficiency and renewable sources of energy.

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