Essential points of the Energy Concept

1. **100% renewables are possible:** Technologies for using renewable energy and energy efficiency have developed more quickly than expected. The remarkable advances show that if the trend towards innovation continues, an energy system which is 100% based on renewable energy can already be realised in Germany by 2050.

2. **A range of options as a guarantor for supply reliability:** The Energy Concept 2050 outlines a reliable, secure, low cost and robust energy supply based on a variety of renewable energies. This range of renew able energies, whose potential is much higher than total energy demand, also ensures that there is a supply of alternatives, if there is a lower contribution or even a "failure" of a technology, so that in any case, supply based on 100% renewable energy is guaranteed.

3. **Energy efficiency is given priority:** The increase in energy efficiency is given the highest priority as a strategic requirement: The institutes advocate a substantial expansion in decentralised Combined Heat and Power (CHP) to increase the energy consumption efficiency of renewable energy conversion techniques – together with the need to further develop incentives for such systems in conjunction with local heating systems. Improving the energy performance of the current building stock will be essentially completed by 2050.

4. **Electricity as a mainstay:** The generation and use of electricity from renewable energy has a central position in the Energy Concept 2050.

5. **European interconnected electricity network:** The transmission of power over long distances by using HVDC, and energy balancing at European level, play a key role in the use of fluctuating energy sources. This wide-ranging balancing via a European power network secures the supply of renewable energy. In addition, the fluctuating supply of wind and solar energy is adjusted to particular demand using energy storage. Renewable-generated electricity thus becomes a primary energy, as chemical energy carriers (hydrogen, methane) are derived from it.

6. **Chemical energy carriers:** In order to form a bridge in longer periods when supply is too low, during these transitional periods these chemical energy carriers can be made available in long-term storage units on a seasonal basis, which amongst other things are needed for the transport sector. The production of"renewable (synthetic) methane" implies a paradigm shift for energy storage.

7. **E-mobility:** Transport in the Energy Concept 2050 is largely supplied either directly or indirectly by electricity, as electricity is converted into hydrogen or methane.

8. **Combined cycle renewable power plant:** The principle of a "combined cycle renewable power plant", with its technical interaction of renewable energy and energy storage, is expanded across Germany.

9. **Avoiding system conflicts:** Today's large power plants are not suitable for balancing fluctuating power from renewable energy, as they cannot cope with the major changes in output that are required for this.

If the priority given to renewable energy during feed-in is retained, then conventional base-load power stations will be increasingly unsuited to supplying residual load. This not only means that neither nuclear power plants, nor fusion power plants, nor coal-fired power plants, can then be used, but also that the current approach of CO_2 capture and storage for coal-fired generation (CCS) is moving in the wrong direction, not only from purely economic but also for system-related reasons.

10. **Role of biomass:** The use of biomass for energy is treated as a limited resource, which means that material and energy applications must be developed. In the medium- to long-term, energy crops should mainly be used to produce synthetic fuels like kerosene for planes and ships, as well as producing raw materials for the chemical industry. Recovering energy from biomass waste supplements this concept.

11. **Solar heat:** In the Energy Concept 2050, solar thermal collectors make an important contribution to heating drinking water, to space heating, process heat and cooling in domestic buildings and for local/district heating and cooling systems.

12. **Costs and use:** With optimum design, economically, the Energy System 2050 will at least be no more expensive than the present system. This is because of the link between technological elements which are described in the Energy System 2050, with their learning and experience effect, and cost/benefit analysis:

    - To begin with, the expansion of renewable energy generates additional costs, both in power and heat production and also in the transport sector. However, with calculations which relate to one specific year, the maximum additional cost is already achieved in 2015, with an amount of approximately 17 billion euro. This only equates to about 8% of total energy expenditure in Germany, which totals 212 billion euro, according to the monetary evaluation of final energy consumption. The argument which says that renewable energy would mean that energy system costs would increase significantly is rejected as a result of this comparison.

    - A calculation of the differential costs of renewable energy from all three sectors clearly shows that the transformation into an energy system which is completely based on renew able energy by the year 2050 is also economically favourable. In the electricity and heat sectors alone, in the period 2010 to 2050, total costs of 730 billion euro can be saved.

13. **Research funding:** The allocation of public R & D expenditure to the different energy technologies must be geared towards their long-term importance. In line with the governing coalition's target and the Energy Concept which has been proposed, the priority should be placed on renewable energy and efficiency in research funding. Research and development should also be used as an industrial policy measure. Only then, when German manufacturers in the field of renewable energy and energy efficiency are global technological leaders, is there the possibility of keeping production of the elements of the new energy supply system in Germany.

1. The Energy System 2050 based on renewable energy

1.1 Developments in global energy demand

In order to limit global warming to a maximum of 2 °C, energy-related carbon dioxide emissions in Europe must be reduced by at least 80 – 95% by 2050. This makes a massive reorganisation of the global energy systems necessary. All global energy scenarios generally assume that above all, renewable energy must be expanded. Because of the clear increase in the global population, as well as the growth in prosperity in developing countries and emerging markets, global energy demand, particularly electricity, will rise significantly. *Figure 1* shows total energy demand to 2030 in megatonnes of oil equivalent (dotted line), based on an IEA forecast. Amazingly, the IEA assumes that the finite fossil and nuclear energy sources will meet this increasing energy demand. However, this is not possible because of the global climate protection goals, which is why this scenario must be regarded as highly unlikely.

In contrast, the Energy Concept 2050 shows how the increased demand for energy services does not have to lead to a further rise in primary energy demand, by consistently applying measures to increase efficiency, and, if growth continues, that renewable energy can meet this demand to the middle of the century.

This means for Germany's energy supply that primary energy demand for power generation can be reduced by about a third of current levels by completely replacing conventional power plants by wind, solar and hydro power plants. This is because every kilowatt hour of electricity from these renewable sources replaces about three times the amount of primary energy that would otherwise be required [13]. For example, the waste heat losses from power generation, which in coal-fired and nuclear power plants cause about 2/3 of primary energy costs, are avoided by using wind and solar power plants.

In industry, there is a particular need for thermal energy at different temperatures.

Part of primary energy demand is avoided by the consistent use of waste heat using thermal storage and heat pumps with a high annual coefficient. Energy storage units are able to

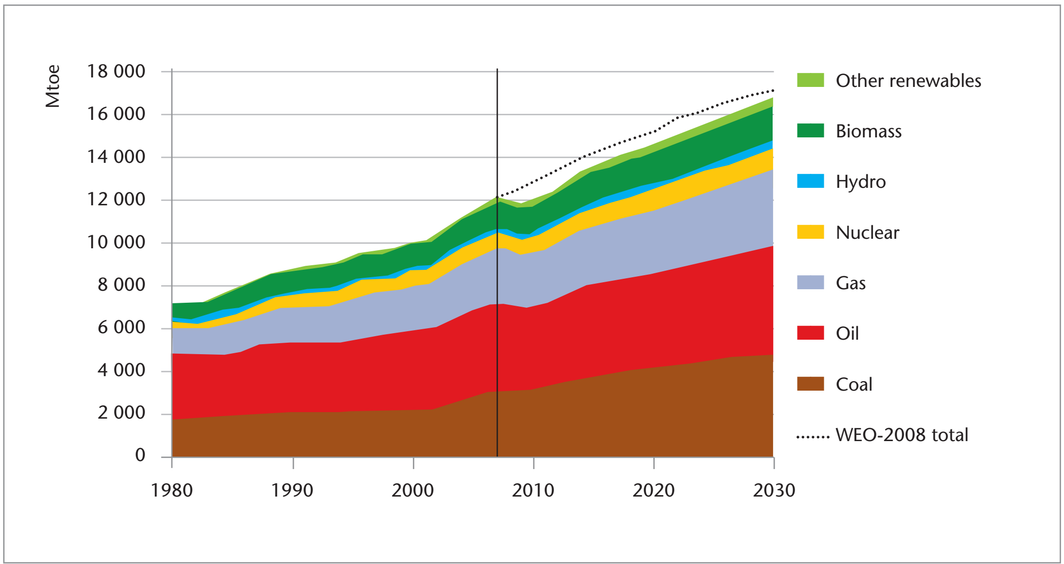
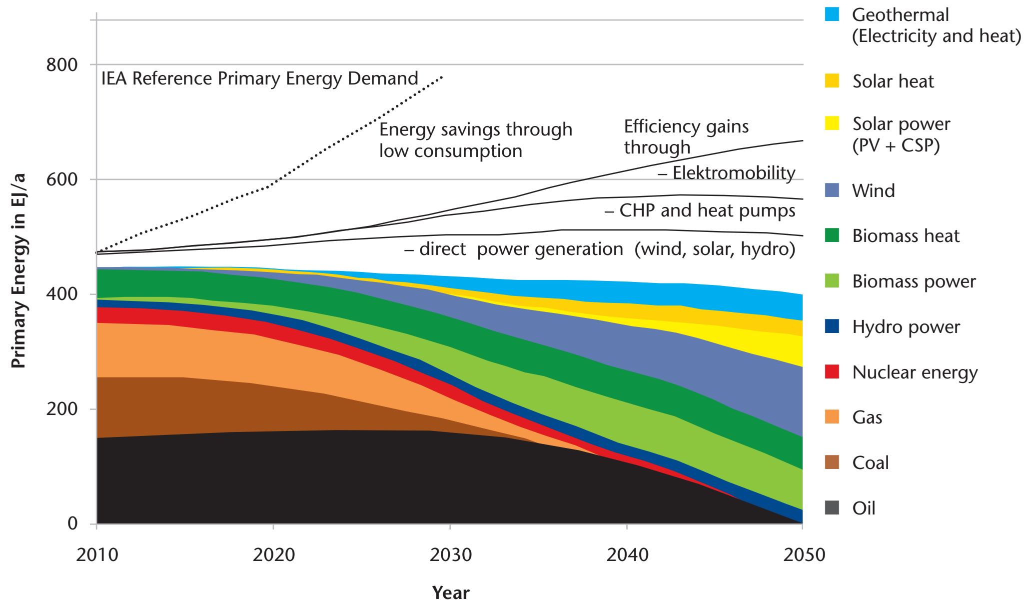


Figure 1
Forecast for growth in global energy demand to 2030 (IEA) and assumptions on possible energy sources to meet demand [12] (12,000 Mtoe = about 500 EJ)

Figure 2
Global scenario for 100% renewable energy: global primary energy demand to 2050 by efficiency method. Energy savings primarily in construction.

PV = Photovoltaic; CSP = concentrated solar power – solar thermal power production).

Source: Fraunhofer IWES (Schmid, Sterner, 2010).



Source: Fraunhofer IWES (Schmid, Sterner, 2010).

absorb the power peaks in the industrial process. Process heat with temperatures of up to 250 °C can also be supplied proportionately by solar thermal energy.

Figure 2 shows an example for a scenario to meet global primary energy demand to 2050 using 100% renewable energy by efficiency method1 and based on the following assumptions: the goal is to develop a pathway to decarbonisation which conforms to the 2 °C limit based on renewable energy without the use of nuclear energy and CCS. Efficiency measures reduce demand for heating and cooling by 1% p.a., and growth in the volume of traffic and demand for electricity is also limited to 1% p.a through efficiency measures.

1 Efficiency methods and replacement methods are used for the primary energy balancing of electricity from renewable energy sources. For fossil energy sources, calorific value is used as a conversion factor, which is a measurement for the useable energy content of a fuel. Then 1 kWh of electrical energy, which is produced in a conventional coal-fired power plant with an efficiency of h = 40%, ismultiplied by a factor of 1/h = 2.5, and is valued in terms of primary energy at 2.5 kWh. Both efficiency methods are valid for 1 kWh of electrical energy, which is produced using hydro power, wind energy or photovoltaics, a plant efficiency of 100%; this energy is therefore valued at 1 kWh in terms of primary energy. For a nuclear power plant with a typical efficiency of 33%, however, 1 kWh of electrical energy is valued at 3 kWh of primary energy.

This means that overall, primary energy demand to 2050 does not rise to above 700 EJ p.a.. Depending on the technology, thehistoric rate of increase in renewable energy (up to 20% p.a.) will continue for a maximum of 20 years. The expansion of technologies with very extensive resources (wind, solar) is managed to saturation, and technologies with limited resources (bioenergy, hydro power) are reduced to zero and therefore restricted in their maximum sustainable potential. The expansion of biomass is limited to a sustainable potential of 150 EJ, and in 2050 it will only be used in the most efficient application for bioenergy, in combined heat and power. The traditional use of biomass in developing countries is also replaced by modern RE technologies [7]. There is only a slight expansion in hydro power. The most difficult sector to decarbonise is the transport sector, which still shows a high dependence on oil. Bio fuels are abandoned for reasons of efficiency and sustainability. [7]. Instead, electromobility is introduced very quickly, as does the use of renewable fuels from wind- and solar-surpluses for special segments of the transport sector (long-distance vehicles, planes, ships, etc.). In 2050, two thirds of energy demand in the transport sector will be met purely by electricity, the remaining third will be met by renewable wind and solar fuels (hydrogen, methane or other renewable-generated combinations of H_2 and renewable CO_2).

The savings and efficiency gains in *Figure 2* result from:

- avoiding waste heat in power generation using direct renewable generation (wind, solar, hydro power)
- efficient drive design for electromobility and expansion in public transport
- Use of ambient heat by means of electric heat pumps
- Use of waste heat in power generation by replacing power plant capacity with combined heat and power capacity
- Implementation of measures to save energy, particularly in relation to heating (insulation, etc.)

1.2 The technological components of the Energy System 2050 and their energy potential

In the future, the technological components of the desired sustainable energy supply, based on renewable energy sources, will, for economic reasons, no longer be divided, according to the previous system plan, into electricity, heat and fuel. Instead, they will increasingly transcend system boundaries. Depending on the systems engineering and systems solutions, the available sources are converted into the energy forms required: heat or fuel is derived from electricity, electricity is produced from heat, and electricity and heat are produced from fuel. When the respective conversion happens depends on the systems solutions requested and the economic conditions..

1.2.1. Energy efficiency technologies

The increase in energy efficiency in primary energy use is given a decisive role because in this way, energy consumption can be substantially reduced without cutting industrial activities or having to give up on comfort, for example in the home.

Heat pumps are an example of such an energy efficiency technology, which offers the possibility, together with renewable power, of supplying buildings with heat sustainably. A further example is electromobility, which can be an efficient and emissions-free alternative, when in operation, for private transport.

Even when the technical energy potential of renewable energy amounts to a multiple of energy demand and therefore savings in consumption do not appear to be necessary, the conversion technologies are linked to costs. However, the reduction in energy demand not only has priority for economic reasons, but also because, particularly in the building sector, lower energy demand has advantages for the use of renewable energy sources [15].

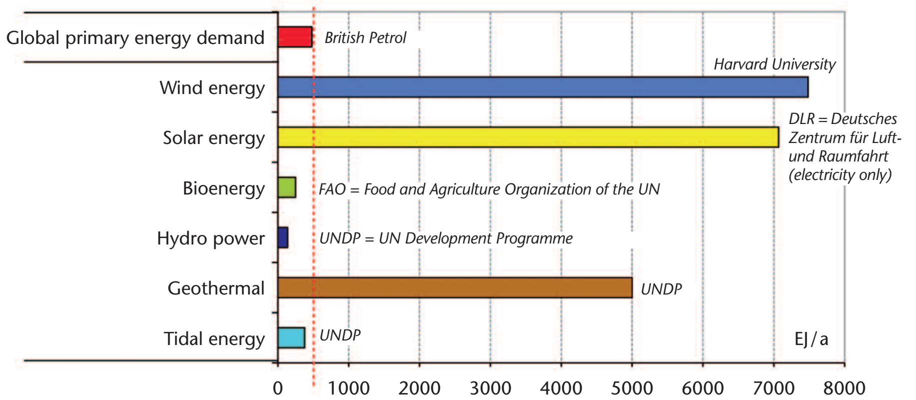
1.2.2. Technologies for using renewable energy

There is sufficient potential from renewable energy to meet current global primary energy demand, *(Fig. 3)*. Just in terms of quantity, the sun and the wind could each meet demand alone, even, but they have a high spatio-temporal variability, there are to a certain extent strong local fluctuations, and they are geographically not adequately available everywhere. The task for research and development is to prepare, technically and economically to develop all renewable energy sources, particularly also with the goal of reducing costs, as well as their integration into energy supply structures and the transformation of energy systems.

A robust Energy System 2050 should ensure that the individual renewable energy potential can largely be covered reciprocally. For this reason it is necessary that the sum of the individual shares of the renewable energy mix amounts to more than 100%. The energy and

Figure 3
Global technical potential of renewable energy (Primary energy by replacement method [2]).

Sources: s. key to diagrams and [18–22]



All the technical potential shown, with the exception of bioenergy and geothermal energy, applies only to power generation. Solar energy is therefore rated somewhat lower than wind energy, as in recent years the potential for wind energy has continued to be adjusted higher in different studies (because of higher hub heights, larger diameters and in particular broader coastal areas for offshore wind). Bioenergy potential (mainly energy crops) is reduced as a result of the assumption of increasing competition for use (food and animal feed, use as a material).[3]

technical potential for Germany and Europe is substantial enough for this. On this basis, the Energy System 2050 can be robust and reliable in order to offset faults and outages caused by fluctuating energy, and ensure full energy supply security.

Electricity, heat and fuels are obtained using different technological options, which can complement and replace each other, as shown for example in *Table 1*.

1.2.3 Energy storage technologies

While fossil and nuclear energy exist in stored form and consequently are always available and can be used flexibly, as part of supply capacity, to meet variable energy demand, apart from biomass and geothermal energy, a renewable system is largely dependent on meteorological and geographical factors.

A wide-ranging balance of renewable energy production achieved by networking secures the supply of renewable energy, and load management can bring together the periods of energy demand with the periods of energy supply. However, for example in the power sector, even when there is a perfect balance using power transmission throughout Europe and load management, there is still a residual demand for storage [23].

1.2.3.1 Storage technologies for electricity

The demand for power storage for energy supply that comes 100% from renewable energy is substantially higher than the storage capacity which is currently available. In Germany, in the winter months, there can be periods with a very low supply of renewable energy (not much solar energy, calm wind conditions because of a Europe-wide Siberian high) [23].

Electromobility also assumes a storage function in a 100% renewable scenario, but even theroetically, it can only meet a small part of demand:

2 Replacement methods value electricity from conventional and renewable sources as comparable: a kilowatt hour (kWh) of wind power replaces the primary energy cost of a kWh of coal-fired electricity (Figure 4).

3 A comparative description and update of the potential of renewable energy will be finallised by the DLR in a study for the UBA in high spatial resolution in 2010.

Energy source	Technology	Primary energy mode	Secondary energy
Wind energy	• Onshore • Offshore	Power generation	Heat Fuel
Photovoltaics	• Silicon wafer-PV • Thin film-PV • Concentrated solar power	Power generation	Heat Fuel
Solar thermal power plants	• Parabolic trough power plants • Tower power plants • Dish technologies • Fresnel collector power plants	Power generation	Heat Fuel
Hydro power	• Barrage technology • Run-of-river technology • Ocean energy	Power generation	Heat Fuel
Biomass	• Polygeneration process	Power generation Heat production Fuel production	
Geothermal energy	• Heat pumps • Deep geothermal energy	Heat production Power generation	
Solar heat	• Passive solar energy use: Transparent heat insulation • Active heat insulation: Solar thermal hot water production and heating • Solar active house, solar local heating systems, process heat and solar cooling	Heat production	

Table 1
Renewable energy sources and the energy demand. If required, power can also be produced again again fuels.

if every 45 million cars have a useable storage output of 10 kWh, only 0.45 TWh would be available, however [24].

The only large storage that exists with the required scale are natural gas storage facilities with an existing thermal capacity of 217 TWh (underground gas storage) and a planned expansion of 79 TWh in the next few years [14]. This technology of long-term storage is proven, safe and established and can be used for chemical energy carriers derived from renewable-generated electricity in two ways: on the one hand direct through the storage of a natural gas substitute in the form of renewable methane, or by adjusting the infrastructure using hydrogen or a mixture (hythane) [25].

- **Electrochemical energy storage**

Electrochemical energy storage takes on increased significance when renewable energy sources are used, as, because of its high energy efficiency, it is ideally suited for buffering fluctuating renewable sources of power such as photovoltaics or wind energy. It absorbs voltage fluctuations, flattens load and demand profiles, allows the use of cable-free or off-grid components and facilitates mobility based on electrical energy. In this context, in the future large stationary batteries, such as for example redox flow batteries, assume an important role.

1.2.3.2 Chemical energy storage

For bridging longer periods when the supply of wind or solar energy is too high or too low, long-term storage is needed, using chemical energy carriers such as hydrogen or methane.

- **Hydrogen**

For the storage of large surpluses, long-term storage technologies (several days or weeks) are necessary. On a large scale, electrical buffering is developed using electrolysis and hydrogen storage in caverns, with downstream power generation by gas turbines. The “surplus” renewable-generated electricity can be stored as chemical energy using electrolysis.

The central point of a hydrogen economy is the ecological and economically justifiable production of hydrogen using different processes:

- Electrolysis from renewable electricity
- thermal water splitting
- Reformation of hydrocarbon fuels (renewable methane)

Renewable electricity can be stored in transportable chemical energy carriers in such as way that it can be used in an offset way, chronologically or spatially. The hydrogen that is produced and stored can thus be used for power conversion to support the network, as well as as a fuel for the transport sector. Efficiency factors of up to 45% are indicated for the entire process chain, (Production, storage and power conversion).[4]

Hydrogen can assume an important role in the future as a clean energy source for fuel and energy supply, because it is very versatile and has advantages: hydrogen can be used in fuel cells, gas turbines (for the production of electrical energy), combustion engines (to produce mechanical energy) or catalytic combustion (heat production) and, last but not least, it can also be used as an intermediate product to produce renewable methane or other hydrocarbons.

- **Renewable methane as a chemical energy store**

In addition to the direct production and use of hydrogen, the Energy oncept 2050 also regards the production of renewable methane as a particularly interesting process for the storage of larger amounts of renewable energy. The advantage compared with a hydrogen world is that the existing gas infrastructure, including power stations, gas networks and also gas storage, can be used for this.

Methane can be directly produced by the reaction of hydrogen with CO_2, via the so-called Sabatier process, which can be supplied to power producers via the existing gas networks and storage. Here, the energy efficiency factor amounts to > 60% ($kW_{Re.methane}/kW_{power}$). This assumes added attractiveness, until now in a 30 kW technology demonstrated process[5] using CO_2 as a raw material. The CO_2 balance is therefore neutral in power stations, biogas plants, the production of synthetic gas or also in cement manufacturing, through the link with methane production.

The existing gas network forms a virtual seasonal store, both for heat and for power generation, and also to supply the transport sector with renewable fuel [26]: While today the storage capacity of the power network amounts to only about 0.04 TWh, – with a storage range of under one hour –, the storage capacity of the existing gas network in Germany amounts to over 200 TWh, with a storage range in the region of months.

1.2.3.3 Thermal energy storage

Storing energy can help to provide constant energy when integrating renewable energy sources with fluctuating supply. The possible range of use of thermal energy storage runs from seasonal storage in solar thermal energy to high temperature storage in solar thermal power generation (Concentrated Solar Power). Even renewable-generated power can be stored cheaply and efficiently after it is converted into heat or cooling, although it cannot be fed into the network in the short-term.

A major contribution towards increasing efficient energy use can be expected from the use of heat in combined heat and power, and particularly from waste heat. By using thermal energy storage, where there is high energy consumption in industry, for example in foundries, cement works or during glass manufacture, large amounts of heat can partly be made reuseable in the form of process heat, or in local

4 If during power conversion waste heat from gas-fired power plants is used, the total efficiency rate increases by 10 – 15 per cent.

5 In an initial technical implementation stage, construction of a 10 MW wind to methane plant, coupled to a biogas plant, is planned, in which biogas is made into methane with no CO_2 separation,by adding H2. The target startup date is 2012.

heat networks to heat buildings and in water heating.

Solar thermal heat can be stored locally, both for power plants at temperatures of over 400 °C, and for domestic water heating, and can be released at the required time.

In principle, thermal energy can be stored in the form of sensible or latent heat, or in thermochemical processes:

- **Sensible storage of of sensible thermal energy**

When storing sensible thermal energy, a storage medium is heated or cooled. In most cases water is used, as it has a high specific heat capacity and is very cost-effective. Smaller stores are used as buffer storage in thermal plants solar (water heating) for storage for days or weeks. Large water storage (up to several thousand m^3) is mainly built in conjunction with a local heating network for the seasonal storage of solar heat, for heating in the building sector. About half the total heat demand for larger building units in Germany can be met by solar power, using large seasonal heat storage.

Heat and cold are also stored in the ground. Here, for example, thermal energy with a temperature level of about 10 °C can be used in winter by a heat pump, and in summer directly to cool buildings.

- **Latent heat storage**

Latent heat storage also applies a phase change in the storage medium to raise temperatures (or to reduce these) (Phase Change Materials = PCM). With smaller temperature differences, therefore, substantially more thermal energy can be stored. This is particularly useful in storage for cooling. In PCMs that are integrated into the building structure, for example, with a fusion temperature of 25°, the ambient temperature can be kept at comfortable levels: When ambient temperatures are over 25°, these materials absorb the surplus energy and thus offer protection against over-heating, when ambient temperatures are lower, they release the stored energy again. PCMs are available at different fusion temperatures. There is currently increased research into new materials which have a high storage capacity, and which are economically favourable.

With combined heat and cooling plants, latent heat storage allows power-led operations.[6] The high specific storage capacity contributes to a compact storage geometry. The use of industrial heat at high temperatures can also occur, or can be made easier using latent heat storage.

- **Thermochemical storage processes**

Reversible chemical reactions can also be used to store thermal energy. This kind of system has high energy storage density, which can be up to 10 times higher than in water, and is able to adjust temperature levels to current requirements when charging and discharging. Most research in this field is on ad- and absorption processes. Here, steam is normally sorbed into solid, microporous adsorbents (e.g. zeolite or silica gel) or into aqueous salt solutions (e.g. lithium chloride). This releases heat. To charge the store, the heat from the steam must again be desorbed.

Open sorption storage is under investigation for application in the use of industrial waste heat. Here, efficient and economically interesting systems could be developed, particularly in the field of industrial drying processes. As well as storage, open sorption storage also offers the possibility to transform heat into cooling, which for example can be used for solar air conditioning for buildings.

6 Because using latent heat storage heat can be stored for use later.

- **Storage required for power-led CHP operation**

Storage for high temperatures for small combined heat and cooling plants facilitates power-led operation, in which the accumulated heat can be stored for up to a few days if necessary. This is also of interest for an improved use of industrial process heat.

1.2.4 Transmission and distribution networks

A European high voltage direct current transmission network (HVDC) is an important component in the Energy Concept 2050. This safeguards national supply by using renewable energy, by balancing production surpluses and production shortfalls in renewable energy within Europe, and by facilitating imports of renewable-generated electricity from North Africa.

Multi terminal HVDC lines[7] allow renewable-generated electricity from desert regions (solar thermal power plants, as in the DESERTEC project, and photovoltaics), and electricity from European on- and offshore wind farms, in conjunction with Scandinavian pump and hydropeaking power plants[8] to be integrated into a European super power network, in which an expansion to eastern and south-eastern Europe can also be contemplated. Close European cooperation is one of the requirements for the gradual increase in the share of renewable energy in the power grid.

HVDC lines do not have any electro-magnetic fields and can therefore to a large extent transport power without losses over long distances. They are also suitable for burying underground, which avoids visual damage and increases acceptance.

Transmission and distribution networks interact both for using energy producer potential, and because of economic considerations, and increase security of supply. The more the cost of renewable energy technologies and smart grids falls in Germany, the more cost-effective is the use of decentralised local energy production and distribution technologies. Importing power from southern Europe, Africa and Norway may not necessarily be more cost-effective, then, but above all it offers an additional energy and technical potential.

Power electronics plays a central role in network control, as the rotary generators in coal-fired and nuclear power plants are not used and the power inverters in wind and PV power plants take over network formation. They control the voltage and frequency of the network through the controlled supply of active and reactive power. If there is a fault on the network, they supply large amounts of short-circuit current to trigger safety devices, and actively participate in rebuilding the network.

1.2.4.1 Decentralised and centralised power and gas distribution networks

The concept is characterised by the following features:

- **Transcending system boundaries:** The different methods of producing methane from renewable energy and the options for use in varying sectors of consumption provide the opportunity for a merger of the energy sectors consisting of the electricity network, the gas network and mobility. Power and renewable methane gas can each be converted to the other in a two-way process, and already have a well-developed infrastructure with seasonal gas storage capacity. In addition, hydrogen can be produced locally from both energy carriers, without being dependent on a large H_2 distribution system with high infrastructure costs.

- **The storage and distribution of temporary surpluses:** in the future there will be increasingly frequent high wind and solar power output because of the further expansion of renewable energy,which cannot be fully incorporated into the power network,

7 Not only point-to-point connections can be realised using HVDC. It is also possible to connect several converters to a voltage circuit. In practice, these systems are mostly called multi-terminal systems. Because of the flexible controllability of the voltage circuit in HVDC Light® Technology – in contrast to the direct current circuit of a network-led HVDC – a multi-terminal system with HVDC Light® is easier to achieve.

8 Hydro power plants in hydropeaking operation to meet peak power demand

but which can be incorporated into the corresponding distribution grids in the form of renewable hydrogen or methane.

- **Natural gas distribution network:** In the current natural gas infrastructure, the renewable-produced, chemical energy source methane is stored, distributed and used to meet demand. About 50%-60% of electricity can be converted into methane, which can again be converted into electricity and heat in existing gas and steam power plants (GaS) or local combined heat and power plants (LCHP).
- **Stabilisation of the power network:** Through the concept "wind/solar energy to renewable fuel", positive and negative balancing energy can be supplied: when there is surplus electricity, the natural gas substitute (renewable methane) is produced, (negative balancing energy), when there is demand for power, the renewable methane is converted into power (positive balancing energy)[9]

This concept could also be implemented using hydrogen, however, a new infrastructure would have to be installed for this.

1.2.4.2 Distributed heating grids

Despite the decreasing demand for site-specific heat in buildings, heat networks can be developed in compact spaces so that there can also be a high proportion of renewable heat there, as well as facilitating the development of CHP. In Scandinavia, heat networks are used with low network temperatures in medium-sized and larger towns as a centralised heat supply structure. Thus there are various possibilities for use in conjunction with combined heat and power and the feed-in of heat from renewable energy, in particular solar thermal energy, as well as waste heat from industry. The installation of heat networks offers a new degree of freedom in the seasonal and spatial management of heat flows, and also in operating plants which generate both electricity and heat. In association with future chillers which are thermally driven by low temperature heat, heat can also be used for air conditioning and can thus reduce electricity demand.

1.2.5 Components for solar and energy efficient construction

The individual technological components which are required to operate an energy supply system 2050, as described in the next chapter, also form the basic elements for solar and energy efficient construction. The interaction of individual production and conversion technologies thus results in quite new system solutions, which can be adjusted to the building's energy demand, to regional characteristics and to climates. The passive house, the solar active house and the energy plus house are each building techniques which use those components from the range of renewable energy and energy efficiency technologies which are the best for a particular building use or region.

1.3 Functionality of energy supply system 2050

After describing the technological primary components and their energy potential in Chapter 1.2, we should now outline the operation of these technological components within a sustainable Energy System 2050.

1.3.1 Power generation as a mainstay of energy supply

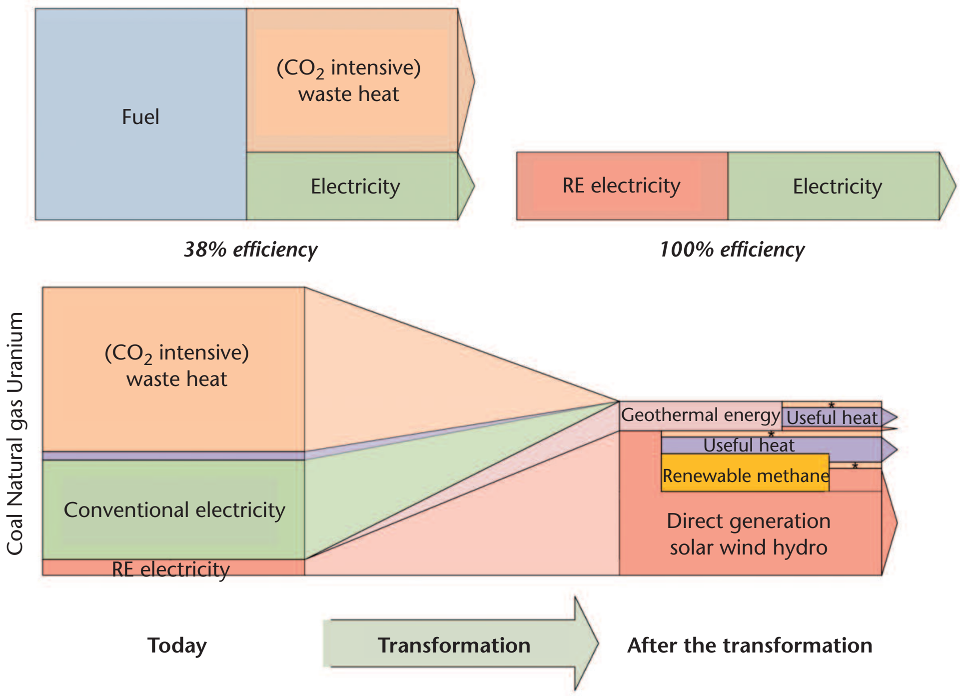
In 2050 wind and solar energy will be the two main sources of power supply, as they have the greatest potential and are amongst the most cost-effective sources of power.

The use of primary energy from purely combustion processes (coal-fired power stations, heating of buildings, the supply of process heat, combustion engines) is replaced by purely renewable electrical systems and renewable generated heat. By using directly produced

9 In 2009, the firms Lichtblick AG and Volkswagen AG started the project "Schwarmstrom", which will network 100,000 gas-fired combined heat and power plants across Germany. These small plants will supply 100,000 buildings with heat and will feed power into the grid. Together they will then form an invisible large 2000 megawatt power plant.

Figure 4
Efficiency gains in the power sector through an increase in direct power generation from renewable energy and combined heat and power (CHP) – an example of transformation.
The diagram is based on the volume breakdown for the 100% RE scenario 2050 (Chapter 2.5.1)
(= CO_2-neutral unused waste heat)*

Source: Fraunhofer IWES



Source: Fraunhofer IWES

With conventional power generation from fossil energy sources without heat extraction, in the global average, only a good third of primary energy can be converted into electricity, while scarcely two thirds remains unused as waste heat. By changing to renewable energy from direct generation, with the same amount of power generation the primary energy demand and energy-related CO_2 emissions thus fall. Waste heat from thermal power generation can largely be made useable by CHP (see also [17]). The stability of power supply is ensured by renewable power generators in a network (combined cycle renewable power plants), energy management (load control) and corresponding storage and backup capacity (mainly pumped storage, gas-fired power plants with hydrogen or with renewable methane).

The illustration is derived from [17, 26].

power generators from wind, hydro and photovoltaic power plants without accompanying waste heat losses, there is a substantial reduction in primary energy demand. This is because in today's power plant mix, every kilowatt hour of electricity from wind, solar or hydro power plants reduces the demand for fossil or nuclear primary energy by about 2.5 kWh.

Solar heat and geothermal energy plants replace fossil heat production. Direct renewable power generation is supplemented by fast reacting gas-fired power plants with combined heat and power, in which the gas used (methane) is obtained from "surplus" renewable generated electricity or from the sustainable use of biomass.

To balance the fluctuations which arise from the direct generation of wind and solar power and for the distribution of energy from the locations with the best generating potential in the consumption regions, both high voltage networks for power (with a share of HVDC) and gas (natural gas and/or hydrogen network) are available [14, 26].

In an overall system which is optimised according to economic criteria, in 2050 the largest share of electrical energy will come from wind power plants, which would be sited in windy locations. In Europe, this is locations along the Atlantic coast, in windy regions inland and in offshore areas. The short- to medium-term fluctuations in wind energy are balanced by a

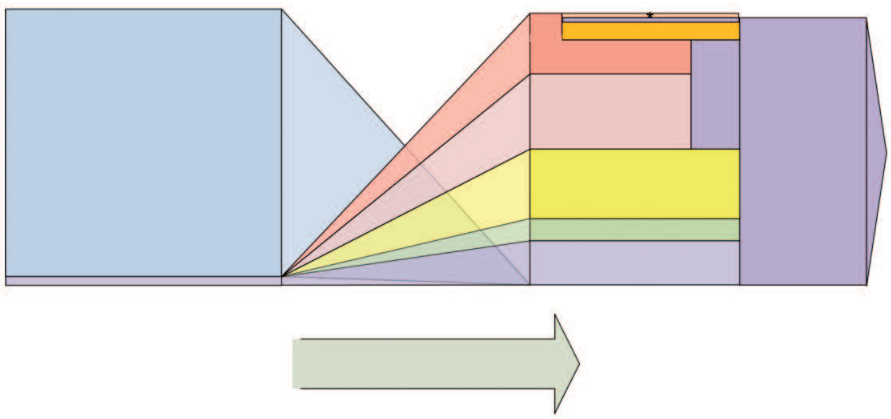


Figure 5
Transformation of the heat sector: by developing combined heat and power, solar thermal energy and the increased use of electric heat pumps, renewable methane/biomethane in condensing boilers and process heat, process and thermal heat demand, which has been reduced by energy saving measures, can in the future be completely met by renewable sources.
The diagram is based on the volume breakdown for the 100 % RE scenario 2050 (Chapter 2.5.1)
(= CO_2 neutral unused waste heat)*

Source: Fraunhofer IWES; the illustration is derived from [17, 26].

European high voltage electricity grid. Seasonal fluctuations are balanced by long-term storage (hydrogen, methane (natural gas substitute)) using the existing gas infrastructure. Wind energy is supplemented by photovoltaics, solar thermal power plants, hydro power plants, which largely exist already today, electricity generated by geothermal energy and combined heat and power.

Solar power plants which operate thermally with heat storage or hybrid supply with the help of chemical energy storage in southern Europe or in North Africa contribute towards balancing fluctuations from wind power generation.

Ocean energy (tidal and wave), geothermal energy power plants for suitable locations, as well as photovoltaic plants that are integrated into buildings, supplement the generation portfolio. Photovoltaic plants take on further functions, in conjunction with combined heat and power and electromobility, to improve security of supply:
If major electrical networks fail, they can enable local networks to operate. For developing and emerging countries, they facilitate the development of decentralised supply networks.

1.3.2 Energy efficiency using combined heat and power

Combined heat and power increases the overall efficiency of conversion techniques and thereby the energy use efficiency of renewable energy. In decentralised energy production, combined heat and power plants will mainly play a supporting role, as will smaller gas-fired power plants, micro-turbines, fuel cells and combined heat and power plants, and fuel cells and micro gas turbines, whose output is adjusted to local heat demand. However, they can also be managed via power demand. With operation at varying speeds, system efficiency rates and life span can be increased. The energy sources deployed come from the use of biomass, hydrogen or methane gas production from renewable energy, solar thermal energy and geothermal energy.

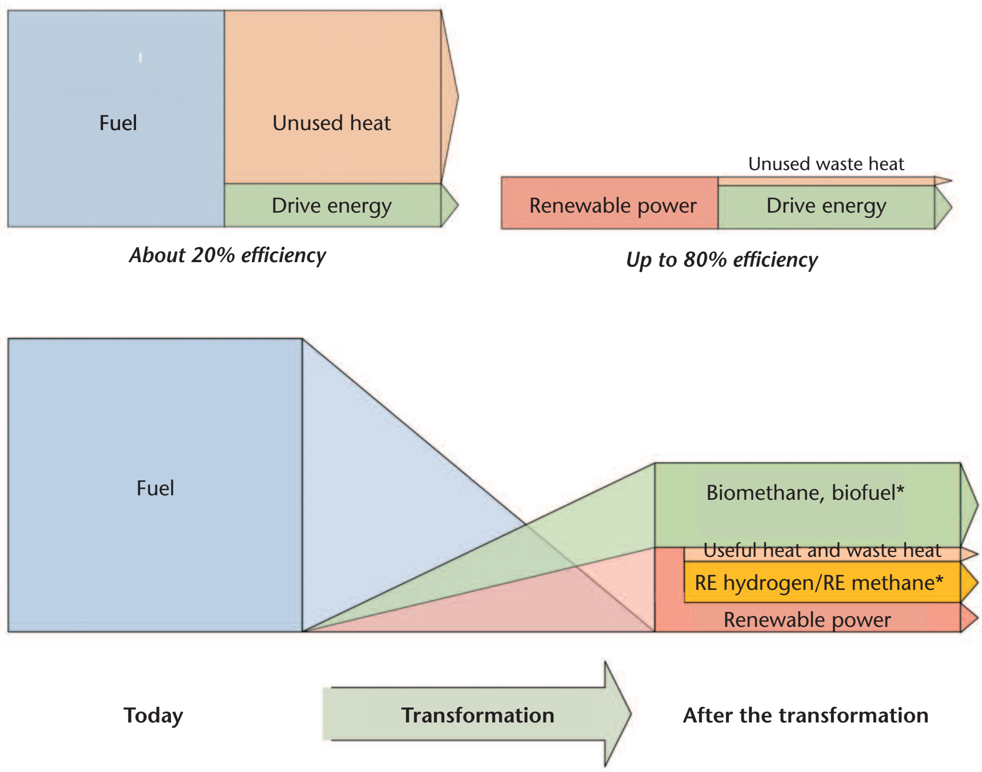
When CHP is combined with solar power generation, both components complement each other extremely well: while in winter CHP produces heat and power, in summer the demand for CHP power is reduced by solar power generation.

The consistent use of CHP, heat pumps and electric drive systems for cars means that overall primary energy demand can be reduced by more than 50% through these three measures alone. These are therefore the most important measures to increase efficiency gains in the energy system. The environmental sustainability

Figure 6
Top: Efficiency gains in the transport sector using electromobility. Comparison between energy cost and efficiency: on the left a conventional drive system using fossil and biogenic fuels, on the right an electric drive system, which uses renewable, directly generated electricity from hydro, solar and wind energy (see also [17]*) Below: Example of transformation: a unit of renewable electromobility, renewable methane/ renewable hydrogen (renewable fuels) and bio fuels (biodiesel, biokerosene).*

The diagram is based on the volume breakdown for the 100 % RE scenario 2050 (Chapter 2.5.1)

Source: Fraunhofer IWES



Source: Fraunhofer IWES

Primary energy demand and greenhouse gas emissions in the transport sector can be substantially reduced. by an increased use of renewable electricity, including a large proportion from direct generation using wind, hydro and solar energy.

* = can also be other renewable fuels such as for example hydrogen or renewable kerosene. The illustration is derived from [17, 26]

of electric heat pumps improves as the share of renewable energy in the electricity mix increases.

1.3.3 Heat production – direct and secondary heat production

The supply of thermal energy is today linked to a very high share of CO_2 emissions. The transformation of heat supply systems therefore takes on a particular importance. Solar heat and geothermal energy plants directly replace fossil heat production and thus avoid the emissions which arise from burning fossil energy sources.

Heat supply for heating buildings results from the interaction of significantly improved thermal insulation and meeting residual heat demand with renewable energy, such as solar thermal collectors, geothermal energy and biomass plants as well as, via waste heat from industrial processes, using combined heat and power (CHP, fuel cells) and by the combination of heat pumps with renewable energy. The supply of industrial process heat primarily takes place using high temperature solar thermal energy, as well as electricity from renewable energy or renewable methane.

The process heat demand for industry and commerce in the temperature range between 80 and 250 °C can be met by renewables. In some sectors, it runs parallel to the supply of solar radiation and can then be met using process heat collectors or CHP plants.

Production figures, which increase in summer e.g. for the drinks industry and the increased demand for cooling in food production and trading, provide opportunities to meet significant amounts using solar power.

That heat demand can be substantially reduced, amongst other things by significantly better insulated buildings, goes without saying. The BMU 2009 lead scenario [9] shows declining demand for heat to 2020 to 85%, and to 2050 to about half current amounts.

1.3.4 Energy supply in the transport sector

Mobility will increasingly happen electrically and will therefore be 2 to 3 times more efficient than today's cars. This includes purely electrically driven cars using batteries with and without "Range extenders", in which the latter can consist of small combustion engines, as well as fuel cells. In freight transport, on the one hand hybrid technologies are also used, on the other, as much freight transport as possible should be diverted to the railways. Renewable fuels (renewable methane, hydrogen, diesel) from biomass, or using power from wind energy, solar energy and hydro power, are produced for freight and long distance transport, for planes and ships.

Cars, trains and buses draw their energy from overhead lines, batteries or fuel cells, so their environmental sustainability is improved by a growing share of renewable energy in the electricity mix. The batteries are charged by bidirectional chargers at charging points. The storage batteries can also be recharged by contactless charging while driving (inductive transmission).

Planes and ships use renewable fuels from biomass, hydro, solar and wind energy. Here it is possible to produce renewable kerosene as a fuel from surplus power according to the process mentioned (renewable methane).

1.3.5 Information and communications in energy supply

Integrating the Energy Concept into an overall European context secures renewable feed-in and reduces the demand for energy storage. Close agreement between all European member states and coordination, for example by the European Commission, is therefore a requirement for successful implementation.

Changing from a centralised energy supply to a decentralised structure with many small fluctuating plants which feed in electricity requires a technical communication link between electricity consumers and decentralised producers in network operation. Only by deploying information and communications technologies can electricity best be distributed or temporarily stored: the power grids become "intelligent", they are called smart grids because they allow bidirectional energy management through the internet. Broadband communications systems between producers, network operators and consumers mean that an online energy market can be created, which enables a flexible alignment between production and consumption through the use of time-of-use electricity tariffs.[10]

In this way, customer-oriented incentive systems can be developed, so that, for example when winds are strong, the batteries of electric vehicles can be charged, or to favour the operation of chillers or heat pumps. The development of current power networks and energy supply structures into smart grids is at present, as part of the so-called E-energy initiative supported by the Federal Government, being promoted and demonstrated in six trial regions.

To balance the sharply increasing fluctuations in power generation from the sun and the wind which will occur in the future, the following elements can be integrated into the online market:

- Decentralised power plants which react quickly – particularly combined heat and power plants or gas, and gas and steam

10 However, data protection must also be taken into account.

power plants, which are supplied via natural gas networks from biomass gasification plants or with methane produced from power surpluses.

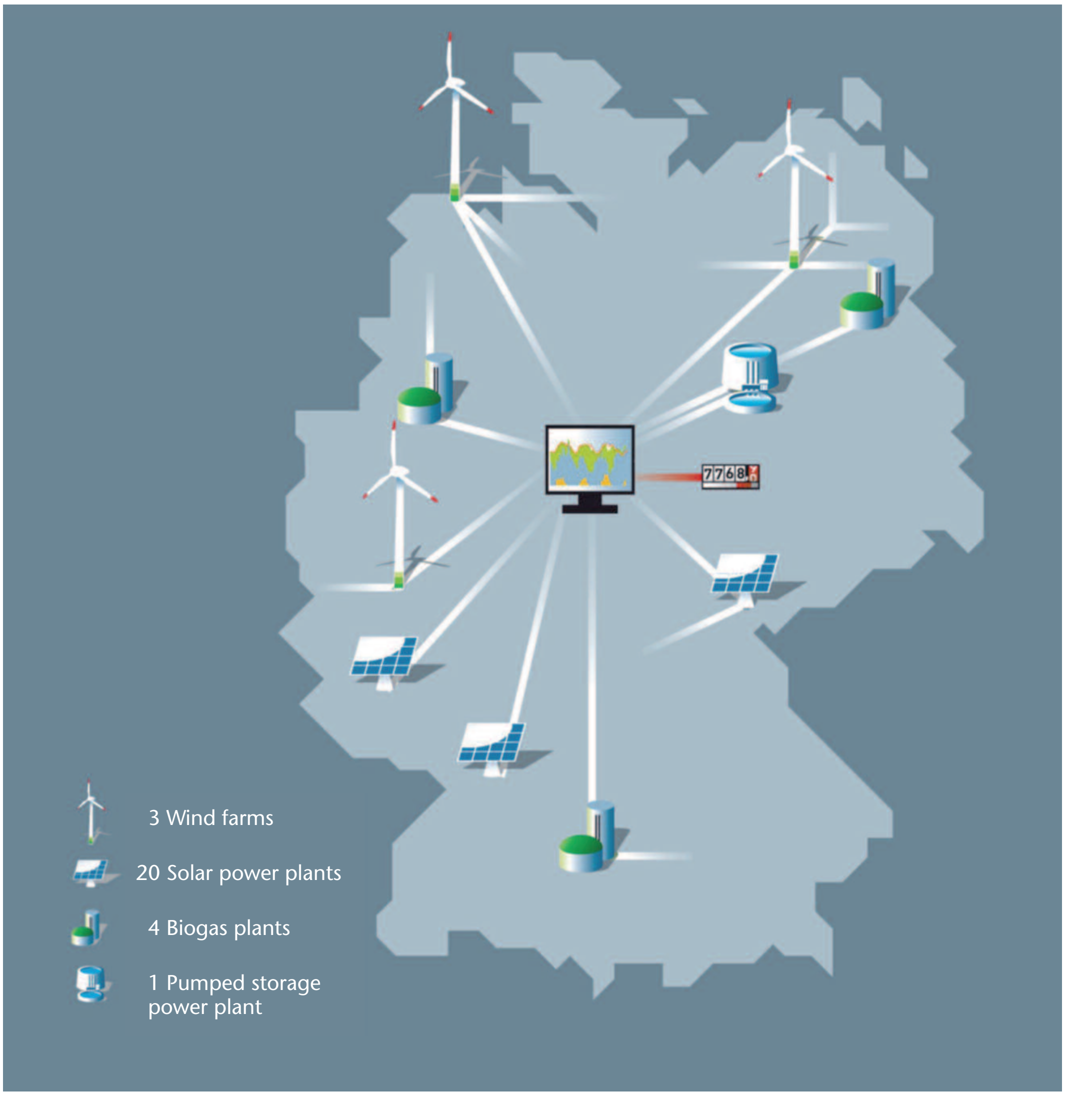
- Interactive networks for electricity, gas and also for heat/cooling (smart grids) in conjunction with smart metering for load and feed-in management (renewable combined cycle power plants).
- Combined cycle renewable power plants for demand-led production from different renewable energy sources, and for the supply of system services for voltage and frequency control.

1.3.6 Combined cycle renewable power plant

The "combined cycle renewable power plant (RKKW)", which was presented at the Energy Summit on July 3rd 2007, showed that a power supply that meets demand from renewable energy is possible through an intelligent link between supply-dependent, producers (wind, PV) which have limited controllability, with controllable producers (biogas-driven combined heat and power plants, micro gas turbines) and pumped storage [27]. This makes a secure energy supply using renewable energy possible at all times and in all locations, particularly if in the future renewable methane is also available in the gas network.

Figure 7
The combined cycle renewable power plant

(schematic diagram)



The combined cycle power plant connects and controls 28 wind, solar and biomass plants which are scattered throughout Germany, with a total output of 23.2 MW [27]. Each individual renewable energy producer has its strengths and weaknesses. Intelligent connection for individual producers, coupled with effective forecasts and combined with storage and flexible consumers, allows output availability which meets the requirements for security of supply. The combined cycle power plant has met Germany's power demand in real time at the ratio of 1:10.000 to the second, and demonstrates that renewable energy is capable of securing Germany's power supply, if it is expanded accordingly.

However, the project has also shown that, for a future energy supply based on renewable sources, installing substantial over-capacity is absolutely essential, so that production surpluses can be generated which can meet temporary generating shortfalls.

The ability of renewable energy to provide reliable supply and to meet total power demand is further strengthened through current research activities as part of the E-Energy Project [28].

1.3.7 Buildings, towns and communities as energy system components

Up to 2050, the passive house, the energy plus house and the solar active house should each in turn become a new building standard. In the long-term, there must be a decoupling of heat energy demand from the per capita living space.

- **Passive houses** are primarily powered by electricity, which is partly produced by a photovoltaic system on the roof, and have a thermal solar power plant for heating drinking water. The remaining energy demand can mainly be met in a highly efficient way through heat pumps supplied by renewable generated power, which can if necessary be used in summer in combination with the PV plant to cool the house. The demand for heat energy in a passive house is up to 15 kWh pro m^2 and per year, the total energy demand amounts to 30 kWh/(m^2a) [9].
- As an annual average, **energy plus houses** can even produce more final energy than they themselves use.
- **Solar active houses**, like passive and energy plus houses, feature good heat insulation and meet their residual heat demand using 100% solar heat, whereby part of the solar heat from the summer can be stored until winter using a seasonal heat storage unit.

In new buildings there is already a movement towards this energy efficient and solar construction method. However, in order to reduce the total level of energy demand in the home, the energy performance of the old building stock must also be improved, which should largely be completed by 2050. This goal would be achieveable with a renovation rate of 2 to 3% a year.

Energy demand in old buildings whose energy performance has been improved is reduced by up to 90% [16]. This can be met by renewable energy. In towns, and in densely populated areas, network and interconnection solutions for the sensible linking of heat sources and heat sinks should be used. In historic monuments, district-based solutions will in particular be used to resolve the situation.

The technology of using local and district heating – possibly coupled with transportable heat stores – takes on a key role in urban centres for the efficient use of waste heat from industry and CHP. Furthermore, synergies can develop by linking old and new buildings, higher flow temperatures are first used in the old building stock for heating, and then new buildings can, for example, always have an adequate supply from the return flow from these systems (cascade use of heat).

1.3.8 Dynamic interaction of technology components

In order to integrate very large amounts of renewable energy, besides the specified high power transmission networks, flexible and interactive distribution and low voltage networks are also needed. These so-called smart grids first facilitate the interaction between generation and consumption and thus open up the opportunity for consumers to adapt to current supply, e.g. via variable tariffs. The first projects to demonstrate the efficiency of so-called smart grids are currently being carried out as part of the E-Energy programme.

Integrating solar thermal power plants into national energy supply offers clear advantages, both in relation to competitive supply and security of supply, as for example described in the "DESERTEC" initiative [29]. On the one hand, operating solar thermal power plants requires a high share of direct solar radiation, which can only be found in southern Europe or in North Africa. On the other hand, this kind of power plant can adapt to particular demand by adding storage units or by operating auxiliary burners, which use renewably produced fuels. However, in each case, these require very efficient long-distance transmission networks. Geothermal power plants must be adjusted to meet demand through optimal use.

If there is no integration of the national power supply using renewable energy into the overall European network, the costs of power supply will rise – also because of the additional power storage units which are required.

So-called residual load power plants will be required in the future to supply balancing energy and control energy to electrical grids, which cover the difference in demand between fluctuating sources of power and current load. In contrast to the base-load power stations, their operating periods are short (e.g. 1000 full-load operating hours/a). However, the requirements for a time dynamic for output supply are very high. For example, gas turbine peak load power stations are well suited for this. A completely new perspective results from the coordinated production of distributed CHP plants as so-called virtual power plants. Here, using appropriate communications equipment, a multiplicity of small CHP plants are then activated when there is a corresponding need for output in the electrical network. Decoupling heat demand, which differs depending on time, occurs using thermal storage units. In exceptional cases, this kind of virtual power station can also come on stream, if there is no heat demand.