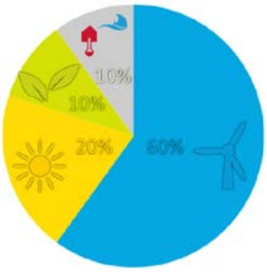
Infoblätter Kombikraftwerk 2

Simulation of a 100% RES System

The Renewable Energy Scenario and the Calculation Results



Percentages of the annual electricity generation in Germany by energy source in the scenario

The Kombikraftwerk 2 research project examines whether a reliable and stable power supply consisting of 100% renewable energy sources will be technically possible in future. For this purpose, a future scenario was developed based on which the required demand for ancillary services and the provision of these services with an intelligent system of renewable generators, energy storage facilities and backup power stations were studied.

The scenario models the future power supply in Germany with 100% renewable energy in unprecedented spatial resolution. This scenario was fed with real weather data and linked with consumption values, creating a detailed idea of electricity generation and transport in every hour of the year. On this basis, the researchers were able to examine the condition and optimisation options for the electricity networks at any given time. Their conclusions: In future, it will be possible in a technically safe way to establish a reliable and stable power supply based 100% on renewable energy, given appropriate adjustments to the system.

In the three-year research project, the project partners from industries and science involved developed this high-resolution geographical model of a power supply system exclusively on the basis of renewable energy sources, and used it for intensive technical feasibility studies and calculations. The study focused on the challenges to grid stability a system of this kind entails and the level of system service demand to keep the frequency and voltage stable with a high percentage of fluctuating generators.

Modelling the 100% scenario

The map of the 100% scenario in detail

In order to examine the stability of a future power supply system, it must be modelled extremely precisely and accurate knowledge is required of which lines are where, as well as how much electricity is generated and where it is fed into the grid and consumed. For this purpose, the Kombikraftwerk 2 research project developed a spatially high-resolution future scenario which maps a power supply with 100% renewable energy sources. It was based on both potential and weather data, current system locations and the German Federal Network Agency's plans for grid expansion.

The scenario assumes that the forecast electricity demand will be met with 60% wind energy, 20% photovoltaics and 10% bioenergy, and the remainder by geothermal energy and hydroelectric power.

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Installed capacity of wind energy in the scenario

Wind energy

The most important sources of energy in the model for Kombikraftwerk 2 are solar, wind and biomass – as in most other 100% scenarios. The locations of wind turbines were primarily generated based on potential sites and weather data. Existing wind turbine locations were also incorporated in the statistical distribution. As the systems are stored in the scenario with pinpoint accuracy, even shading effects within the wind farms are taken into consideration for energy generation. In total, five different wind turbine types are assumed and distributed based on the location. Offshore wind power utilises all presently zoned areas in full. Onshore a far higher installation capacity than assumed would be possible. Overall, wind energy in the scenario reaches the following capacity figures and energy yields:

Wind energy	Onshore	North Sea	Baltic Sea
Installed capacity (GW)	87	36	4
Full load hours	2584	3907	3463
Annual energy yield (TWh)	225	141	14

Photovoltaics

To position and design photovoltaic systems, the actual construction in Germany stored in the scenario was incorporated (broken down into flat and pitched roofs as well as façades), as well as the transport infrastructure (motorways and railways). Only part of the technically possible potential was used for photovoltaics, too. As a result, scenarios with far higher capacities and energy yields would be conceivable. It is also assumed that every third PV system on roofs or building walls is equipped with a battery to store PV energy surpluses. In detail, the various forms of photovoltaics achieve the following figures:

<table>
<tr><th>Photovoltaics</th><th>Pitched roofs</th><th>Flat roofs</th><th>Façades</th><th>National motorways</th><th>Railways</th></tr>
<tr><td>Installed capacity (GWp)</td><td>70</td><td>13</td><td>5</td><td>15</td><td>30</td></tr>
<tr><td>Full load hours</td><td colspan="2">909</td><td>605</td><td>942</td><td>947</td></tr>
<tr><td>Annual energy yield (TWh)</td><td colspan="2">75</td><td>3</td><td>14</td><td>28</td></tr>
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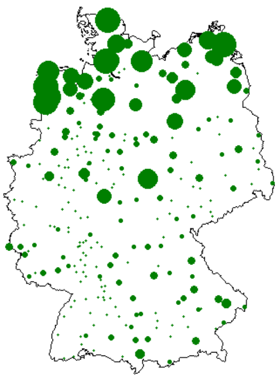
Bioenergy

Bioenergy as the third-largest energy source is primarily used to supplement the fluctuating energy sources wind power and solar energy. The scenario distinguishes between 10 different bioenergy forms which are converted into electricity in a variety of ways. The following table specifies the usage applications and energy yields:

Bioenergy	Annual energy [TWh el]		Local potential	Conversion in:
Biogas	Energy plants:	10.2	On fields and meadows	Bioenergy plants & methane power stations (40% locally in villages, 60% via natural gas network)
	Fertiliser:	14.1	In villages	
	Private sewage gas	1.3	In settlement areas	Bioenergy plants & methane power stations (40% locally in industrial areas, 60% via natural gas network)
	Industrial sewage gas	0.3	In industrial areas	
Solid biomass	Energy plants	6.0	On fields	Local bioenergy plants in villages
	Residual forest timber	12.2	In forests	Wood-fired heating power stations (approx. 40% via gasification in the natural gas network)
	Waste wood	9.1	In settlement areas	Waste wood power stations (approx. 60% via gasification in the natural gas network)
	Biogenic waste	5.9	In settlement areas	Waste-to-energy plants
Liquid biomass	Energy plants	1.5	On fields	Local bioenergy plants in villages
	Total	60.5		
	Of which biomethane	26		

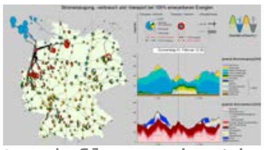

Modelling the distribution of power-to-gas plants

Hydroelectric power

An energy contribution of 25 TWh is assumed for hydroelectric power. The increase over present rates is largely due to the modernisation of existing power stations rather than the construction of new plants.

Geothermal energy

For geothermal energy, it is assumed that the systems can only be operated profitably with combined electricity and heating use. With this premise, a geothermal electricity generation potential of 66 TWh annually is present, of which roughly 60 percent is utilised in the scenario. That corresponds to an annual electricity generation of 40 TWh. The power stations were distributed geographically evenly to the regions which are suitable for geothermal electricity generation, i.e. primarily in the North German Basin, the Upper Rhine Valley and the South German Molasse Basin.

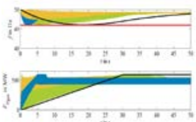

Load flow animation to visualise generation, consumption and grid load

Storage systems

In addition to pumped-storage power stations and batteries, power-to-gas, the conversion of excess electricity from renewable sources to methane (RE methane) was assumed to be the most important form of energy storage. The performance of the power-to-gas plants was determined as a compromise between the storage capacity required to store all excess electricity and commercial considerations. The scenario plans power-to-gas plants with a capacity of roughly 13 GW. Decentral CHP stations and central gas power stations, grouped under the heading “Methane power stations”, can convert the RE methane and the biomethane produced in biogas plants into electricity, which allows them to act as reserve power stations for times with little sunshine and wind. In a high-load hour with little generation from wind and solar power, the methane power stations in the scenario generate their maximum value of 43 GW. The power-to-gas systems and the methane power stations required to convert the gas back into electricity were positioned based on the needs of the supply system, whereby the demand for storage capacity by converting excess (offshore) wind energy to methane is largely in the north of Germany, while the methane power stations are distributed near the consumption centres throughout Germany. The use of power-to-gas is a model assumption. Other scenarios could also include more extensive use of alternative storage technologies or increased linkage of the electricity and heating or transportation sector.

Electricity consumption

In order to determine the transport of electricity, the generation locations and the consumption locations are critical. The basis for the electricity consumption modelling in the scenario was present-day consumption data, which was corrected downwards due to increasing energy efficiency on one hand, while on the other additional consumption was added due to the increasing use of air conditioning systems, electric vehicles and heat pumps. A total annual consumption of 532.3 TWh resulted. Added to this was 36.6 TWh of storage losses to store a total energy of 68.9 TWh. The consumptions were distributed geographically in accordance with the present-day distribution in industrial, commercial and residential areas and in accordance with the storage locations, and for grid losses, the electricity lines.


Evaluation of the dynamic frequency changes in the simulation

Grid modelling

The model’s electricity grid was assumed on the basis of pilot scenario B 2032 of the Federal Network Agency, which is to be implemented by 2032. In particular, the high-voltage direct current (HVDC) transfer lines, which have yet to be built, will play an important role. Based on this grid, the project also studied whether additional expansion measures are required for stable operation of the 100% renewable energy system. The results were that to guarantee grid stability (n-1 secure), comparably few additional construction measures are required beyond the improvements already planned by 2032, in order to operate this power supply system based exclusively on renewables reliably and stably. However, comprehensive redispatch measures are required regularly to adapt the use of power stations to the restrictions of grid operation. Greater grid expansion can reduce the redispatch demand.

The subordinate distribution grid was not considered in further detail in the project. An exchange with other countries was assumed, whereby the energy export/import balance was even for the entire year in question, and exports or imports are only possible when there is demand or excess in the respective neighbouring countries.

Results of the calculations

Frequency maintenance

Two different mechanisms were studied in the project for frequency stabilisation. The main short-term frequency change is the result of a sudden failure of a large generator. For this, the project assumed the failure of the largest power station in Europe as today. Initially after the failure, the missing energy in the system is taken from the rotating masses of the synchronous generators in thermal and hydroelectric power stations, which delays the frequency drop. After this passive stabilisation mechanism, the primary control reserve must come from the intended power stations within a few seconds. They immediately feed in more power, stabilising the frequency again. These properties were simulated for all time steps with the generators connected to the grid and an optimised distribution of the provision of control reserve on currently possible units. If the period to full provision of control reserve remains at the currently required 30 seconds, the frequency after a simulated power station failure often drops too low in many cases with high RE feed-in. The reason for this is that the inverter-connected generating systems such as wind and solar energy cannot provide rotating mass for the grid with the current operating mode. However, by simulating far faster reaction times for solar and wind energy, power-to-gas systems and batteries, this challenge for an exclusively renewable power supply system was solved. In order to use the faster reaction times, the regulatory framework for the control reserve activation times must be shortened. Technically, rapid draws from the abovementioned systems are already possible today, allowing renewables to compensate for the lack of rotating mass. With this measure, the simulations revealed that stable, reliable frequency properties could be proven at all times, even in the event of the greatest of assumed failures.

Another study by the project was the dimensioning of control reserve reserve types which come at later times – secondary and tertiary control reserve reserve. After frequency fluctuations are absorbed by primary control reserve, they return the frequency to the nominal value in between 30 seconds and one hour, and allow the primary control reserve to react to further fluctuations. While the short-term generation fluctuations will continue to be determined by the failure of large power stations or lines, the somewhat slower fluctuations are significantly affected by fluctuations in the nationwide supply of wind and solar power. In a future 100% renewable system with almost full electricity generation from wind and solar power at times, the total fluctuations expected will be extremely large, and a lot of secondary and tertiary control reserve reserve would have to be maintained with high economic costs. In order to counteract this effect, the project studied dynamic reserve capacity dimensioning. By contrast to the current system in which the control reserve reserve required is calculated in advance for a quarter of the year, and therefore has to be based on the worst possible case, dynamic control reserve dimensioning determines the short-term fluctuations to be expected every day based on the feed forecasts for every hour of the following day. On average, the dynamic control reserve dimensioning resulted in roughly the same demand for secondary control reserve and minute reserve as today. If the current method of dimensioning demand were retained, the demand for control reserve would roughly double.

Voltage maintenance

Besides the frequency, the voltage is also a key factor in determining the system stability. For grid stability, it is essential that the voltage present at every grid node does not exceed or fall below the target value by more than 10 percent. The research project only investigated the transfer grid level, i.e. the 380 kV and 220 kV voltage levels. In order to correct voltage deviations in the alternating current grid, reactive power is required which must be provided locally. In the scenario, the reactive power previously provided by large-scale power stations is provided by a variety of different system types of various sizes and locations (central/decentral), which interact with one another. Even with this wider distribution of the provision of reactive power in the simulation, no critical voltage deviations resulted. However, to optimise the results, the renewable energy systems should be connected to the highest voltage levels possible. Ideally, a certain proportion should also be provided by central systems (larger RE farms, storages, reserve power stations). The provision potential for reactive power from subordinate voltage levels can be increased in particular via tapped transformers, which would also improve voltage maintenance in the distribution grids that were not examined in the project. Just a few additional reactive power capacitors can compensate some remaining local reactive power deficits which cannot be directly covered with generating systems. For this purpose, converted former power stations such as the one already operating in Biblis, or plants already available today optimised for this purpose, can be used.

Summary and measure recommendations

The calculations show that a power supply based 100% on renewable energy is possible in a technically secure way in Germany in future, and that with appropriate adjustments to the system, the customary high supply quality need not be compromised to implement the German energy transition (‘Energiewende’).

However, the system requires large storage capacities for full supply with renewable energy in the electricity sector. They must also be suitable for providing ancillary services. Storage use, grid expansion, scope of redispatch measures and the use or capping of energy surpluses are mutually dependent on one another – there are significant influencing options for the design of a 100% renewable power supply scenario. An installed capacity of bioenergy and methane power stations at roughly the same level as the maximum load should be available in any case. For a full supply from renewable sources, the decentral systems absolutely must be networked, for example as virtual power plants, to compensate for frequency and local voltage fluctuations system-wide and in coordination.

In future, the control reserve reserve should be dimensioned dynamically based on the forecast feed-in situation to prevent further increases in demand. The activation time for primary control reserve should also be differentiated based on the energy source to compensate the reduced rotating mass with the technically feasible faster reaction times of wind and PV systems. Under these conditions, the frequency can be maintained at all times in the 100% RE scenario without problems. The proof of provided control reserve for fluctuating feed-in sources such as wind and solar energy should be switched to the “available active power” method (see Field Test Background Paper), instead of the previous comparison with the roadmap calculated from forecasts used today. That allows the systems to make the most of their potential capacity.

With a mix of central and decentral systems, voltage maintenance was guaranteed at all times in the simulation. For additional local reactive power demand, e.g. in conurbations, it may be necessary to use some supplementary compensation systems. To optimise the provision of reactive power, the renewable energy systems should be connected at the highest voltage levels possible. Inverter-controlled systems should be able to contribute to voltage maintenance even if they are not producing electricity at the time in question.

Background & contact
The three-year “Kombikraftwerk 2” research project is funded by the German Federal Ministry for the Environment. The consortium partners are: CUBE Engineering GmbH, German Weather Service, ENERCON GmbH, Fraunhofer Institute for Wind Energy and Energy System Technology, ÖKOBiT GmbH, Institute of Electric Power Systems of Leibniz University Hanover, Siemens AG, SMA Solar Technology AG, SolarWorld AG and German Renewable Energies Agency.

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