Integration Of Large Scale Wind Parks Into The Grid And Their Impact On The Development Of The Future Power Station Park

Torsten Haase, Thomas Hamacher, Harald Weber

Abstract. The increase of wind energy is the declared goal of the German government to reduce the CO_2-emissions. Up to the year 2030 the on- and offshore wind capacity will sum up to about 48 GW. By then the energy supply in Germany will change to an energy supply led by the stochastically arising energy offer by wind power plants. In order to compensate for the fluctuating feeding from the wind power plants fast backup power plants are needed. The wind energy is mostly produced in northern Germany, but is mainly needed in southern Germany. Therefore additional transmission capacities are required. A simplified economic model of the German energy generation and transmission system was used for this investigation. The technical feasibility of the optimised power station park and grid was investigated by means of network calculation. Based on these models a possible scenario of the energy supply in Germany in the year 2030 will be discussed.

Keywords

Wind energy, bottlenecks, substitution of conventional power, economic optimization, network calculation

1. Introduction

This paper deals with the economic and technical demands which must be met in the future by an energy supply characterized by the wind energy in Germany. Using today's findings of the network calculation it will be possible to examine the integration of wind farms into the net within the next years with realistic models.

The investigations were based on detailed technical power plant models and grid models which have been verified by way of measuring. The study was also based on economic power plant models which have been provided with realistic parameters. In this paper the minimal costs for the investments and for the operation of the German integrated grid for the year 2030 have been calculated with a linear minimum-cost model. The wind energy which is expected in 2030 was included into the economic optimization. The following questions shall be answered by the optimization:

- Are the wind power plants able to cover the base-load in the year 2030 and thereby substitute the thermal power station capacity?
- How much fuel can be saved by means of this substitution and can this lead to a considerable reduction of the CO_2-emissions?
- At which sites in the transmission system can new power stations for coal or gas be installed cost-effectively?
- Where do bottlenecks arise in the high-voltage transmission system and how many transmission capacities must be built then?

Afterwards, the technical feasibility of the optimised power station park and German grid was investigated by means of network calculation and simulation.

2. Development of the Onshore and Offshore Wind Energy until 2030

An enormous boom for the construction of onshore wind power plants was caused by an attractive remuneration of the wind energy fed into the grid as well as the obligation to accept delivery of wind energy according to the German renewable energy law and the rapid technical development starting afterwards. By the end of 2006 wind power stations with an output of 20,622 MW were installed in Germany. The wind

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	Wind Farm	Pilot Phase	Development	Location	Permission
1	Butendiek		240 MW	North Sea AWZ	12/2002
2	Dan-Tysk	400 MW	1.500 MW	North Sea AWZ	08/2005
3	Weiße Bank		600 MW	North Sea AWZ	at pres. not pursu.
4	Nördlicher Grund	360 MW	2.195 MW	North Sea AWZ	12/2005
5	Sandbank 24	400 MW	4.720 MW	North Sea AWZ	08/2004
6	Globaltech I	360 MW	1.440 MW	North Sea AWZ	05/2006
7	Nordsee-Ost	400 MW	1.250 MW	North Sea AWZ	06/2004
8	Amrumbank West		400 MW	North Sea AWZ	06/2004
9	Meerwind	280 MW	819 MW	North Sea AWZ	04/2004
10	Hochseewindpark Nordsee	536 MW	2.286 MW	North Sea AWZ	07/2006
11	Hochseewindpark He dreiht		536 MW	North Sea AWZ	08/2004
12	Borkum Riffgrund West	280 MW	1.800 MW	North Sea AWZ	02/2004
13	Borkum Riffgrund	231 MW	746 MW	North Sea AWZ	02/2004
14	Borkum West	60 MW	60 MW	North Sea AWZ	11/2001
15	North Sea Windpower	240 MW	1.255 MW	North Sea AWZ	02/2005
16	Uthland		400 MW	North Sea AWZ	at pres. not pursu.

	Wind Farm	Pilot Phase	Development	Location	Permission
17	H2-20		400 MW	North Sea AWZ	at pres. not pursu.
18	Riffgat		200 MW	North Sea 12 SMZ	03/2006
19	Dollart		5 MW	North Sea 12 SMZ	10/2004
20	Nordergründe		125 MW	North Sea 12 SMZ	12/2003
21	Wilhelmshaven		5 MW	North Sea 12 SMZ	Future openly
22	Beltsee		415 MW	Baltic Sea AWZ	at pres. not pursu.
23	Kriegers Flak I		321 MW	Baltic Sea AWZ	04/2005
24	Ventotec Ost 2	240 MW	600 MW	Baltic Sea AWZ	09/2005
25	Arkonabecken Südost	400 MW	1.005 MW	Baltic Sea AWZ	03/2006
26	Gode Wind	320 MW	896 MW	North Sea AWZ	09/2005
27	Bard Offshore I	400 MW	1.600 MW	North Sea AWZ	02/2006
28	Sky 2000		150 MW	Baltic Sea 12 SMZ	12/2003
29	Rostock		207 MW	Baltic Sea 12 SMZ	at pres. not pursu.
30	Breitling		3 MW	Baltic Sea 12 SMZ	02/2006
31	Baltic I		54 MW	Baltic Sea 12 SMZ	08/2004

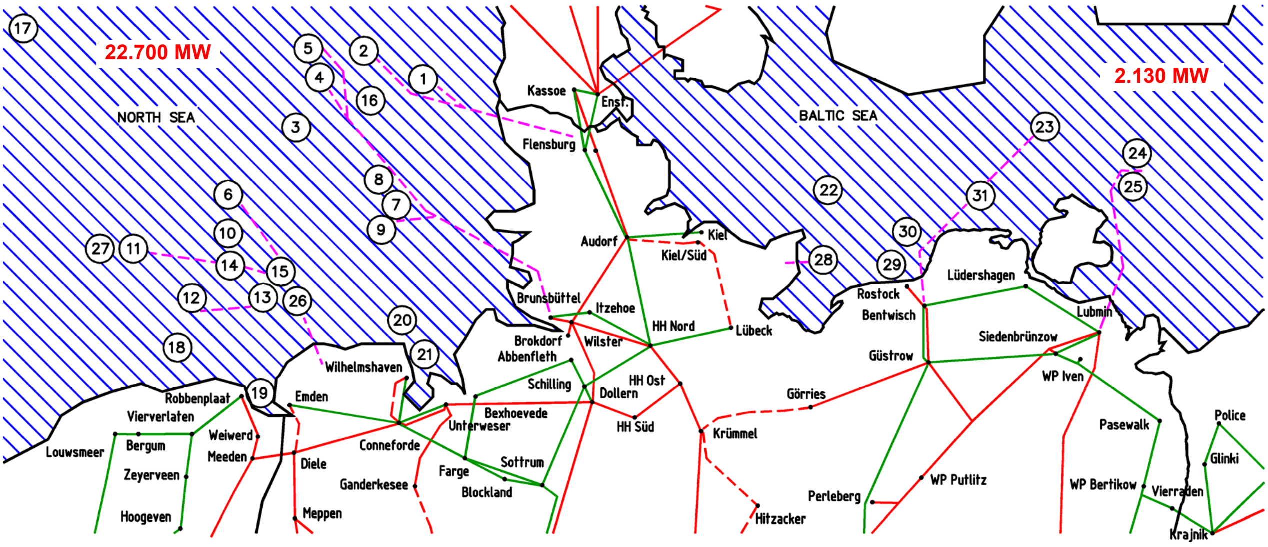

Fig. 1. Planned German Offshore Wind Farms

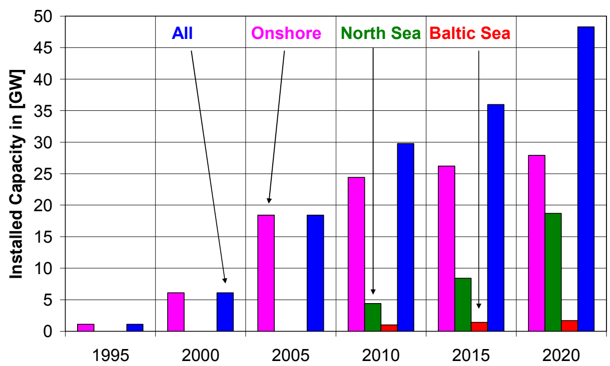

Fig. 2. Historic and expected development of the German onshore and offshore wind energy capacity

energy production amounted to approx. 30 TWh (E.ON 12.7 TWh, Vattenfall Europe 11.3 TWh, RWE 5.6 TWh and EnBW 0.4 TWh) in the year 2006. This development will continue and the annual rates of increase will turn out lower due to the restricted productive onshore sites. Starting from the year 2010 the rise of the wind energy production will be caused only by the replacement of older plants by more efficient and more productive plants. For the year 2020 an installed onshore wind power with approx. 27.9 GW is forecasted. The difficulty will be to maintain the extension of the wind energy use in Germany on high standard even though there will be a saturation in the onshore area. The solution will be to gradually acquire suitable sites at sea. For these sites in the North Sea and the Baltic Sea investors have applied for 31 wind parks depicted in Fig. 1. which partly consist of several hundred single wind power plants. At present, wind parks are planned with an installed power of 22,703 MW in the North Sea and 2,130 MW in the Baltic Sea. Fig. 2. gives an overview over the historic and expected development of the German onshore and offshore wind energy capacity.

3. Wind Model

Wind power shows very special characteristics, which differs considerable from conventional power plants. The following investigations are based on wind data collected on the world wind atlas (Sander + Partner GmbH, Switzerland). The data presented on the world wind atlas has only a six hour time resolution. By special random methods also data with one hour time resolution were produced. The transformation from wind velocity to active-power output was done with data from modern existing wind turbines for onshore sites (1 MW, 1.5 MW, 2 MW) and offshore sites (2.5 MW, 3 MW). Supply of power from wind turbines is stochastically in nature, the actual active-power output is more or less proportional to the third power of

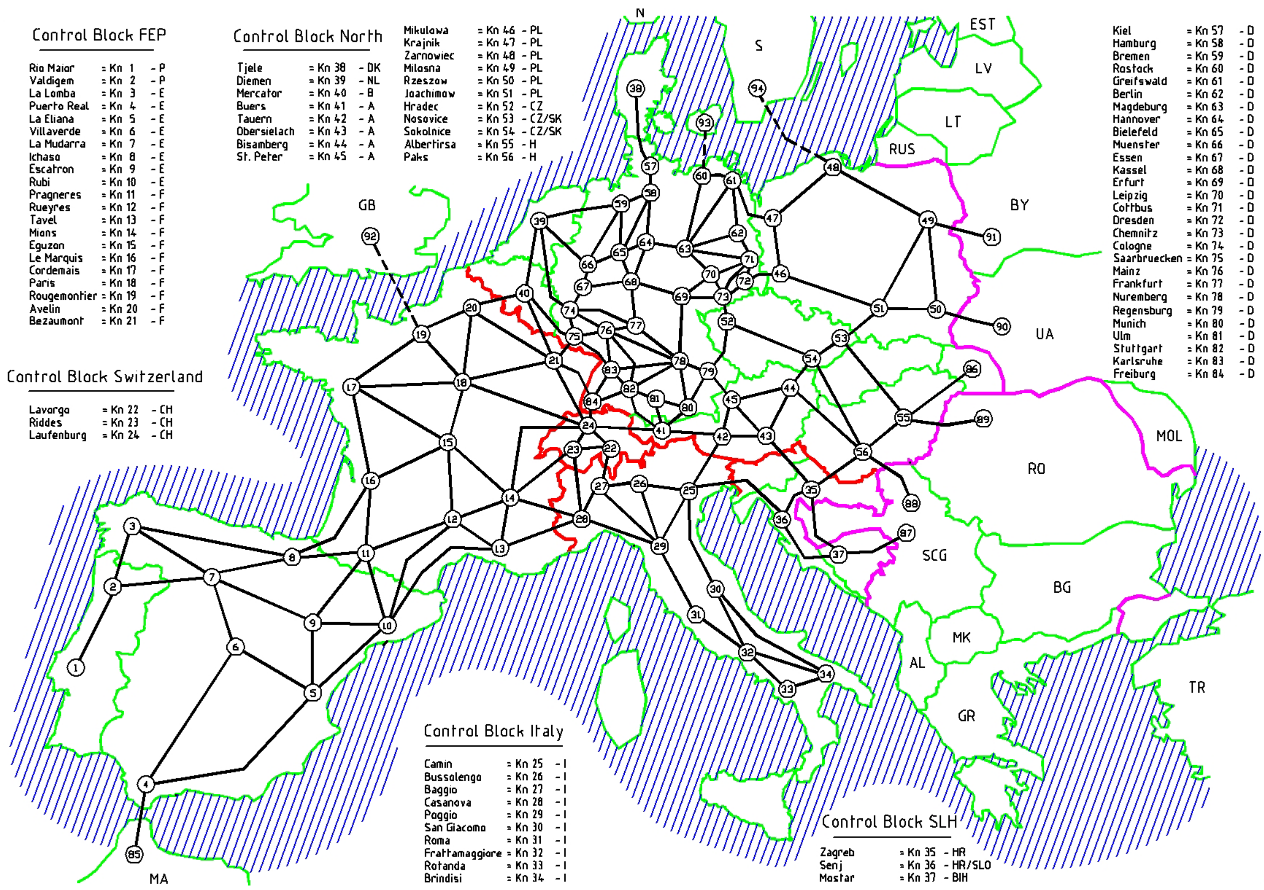

Fig. 3. Reduced Network Model for calculation

the actual wind velocity (P~v³). The wind velocity depends on the location and the actual meteorological situation, which itself depends strongly on the season. It is noticeable, that the average wind velocity in the North Sea is considerably greater then in Southern Germany. This means, a profitable and economic wind energy production is possible only in the north part of Germany, especially offshore. The wind power plants installed in December 2003 in the German federal states were distributed among the network nodes. It was scaled to the onshore installation of 22 GW in the year 2030. The estimated offshore installation of 26 GW in 2030 was distributed to the network nodes in the immediate coastal area. In the year 2030 the wind current production would amount to 118.6 TWh with an offshore share of 69.2 TWh. Then the quota of wind energy in the total electricity generation of Germany will be up to 21 %.

4. Network Model

In the network model the German production and consumption centres are represented by 30 substitute nodes. The power stations belonging to the consumption centres were summarized and subdivided according to their sources of energy or their mode of operation (coal, natural gas, pumped-storage, run-of-river). Special attention was paid to the modelling of the pumped-storage power stations because these plants are the only ones which are presently able to store energy with a high efficiency (> 75 %). Exact data were provided by the operators of the pumped-storage power stations in order to be able to determine the energy capability as well as the average power in the pump and turbine operating mode. The calculated total energy capability of the pumped-storage power stations in the turbine operating mode amounts to approx. 43.3 GWh and in the pump operating mode to approx. 56.7 GWh. The electrical consumer loads were taken from a UCTE data set and assigned to the respective substitute nodes. The consumer loads of every node were subdivided into 84 typical diurnal variations. These variations represent one week of each month of the year. It was calculated from Monday to Sunday because every day of the week has a specific characteristic. In order to model these characteristics the calculation was realized in a one-hour resolution. Among other things the calculation of the curves was based on the load of the four German energy supply companies of the year 2003. Then they were scaled to the consumption expected for 2030. The transmission capacities between the substitute German nodes in the 380/220-kV level were determined and summarized from a detailed model of the UCTE net. The surrounding UCTE net was modelled in simplified

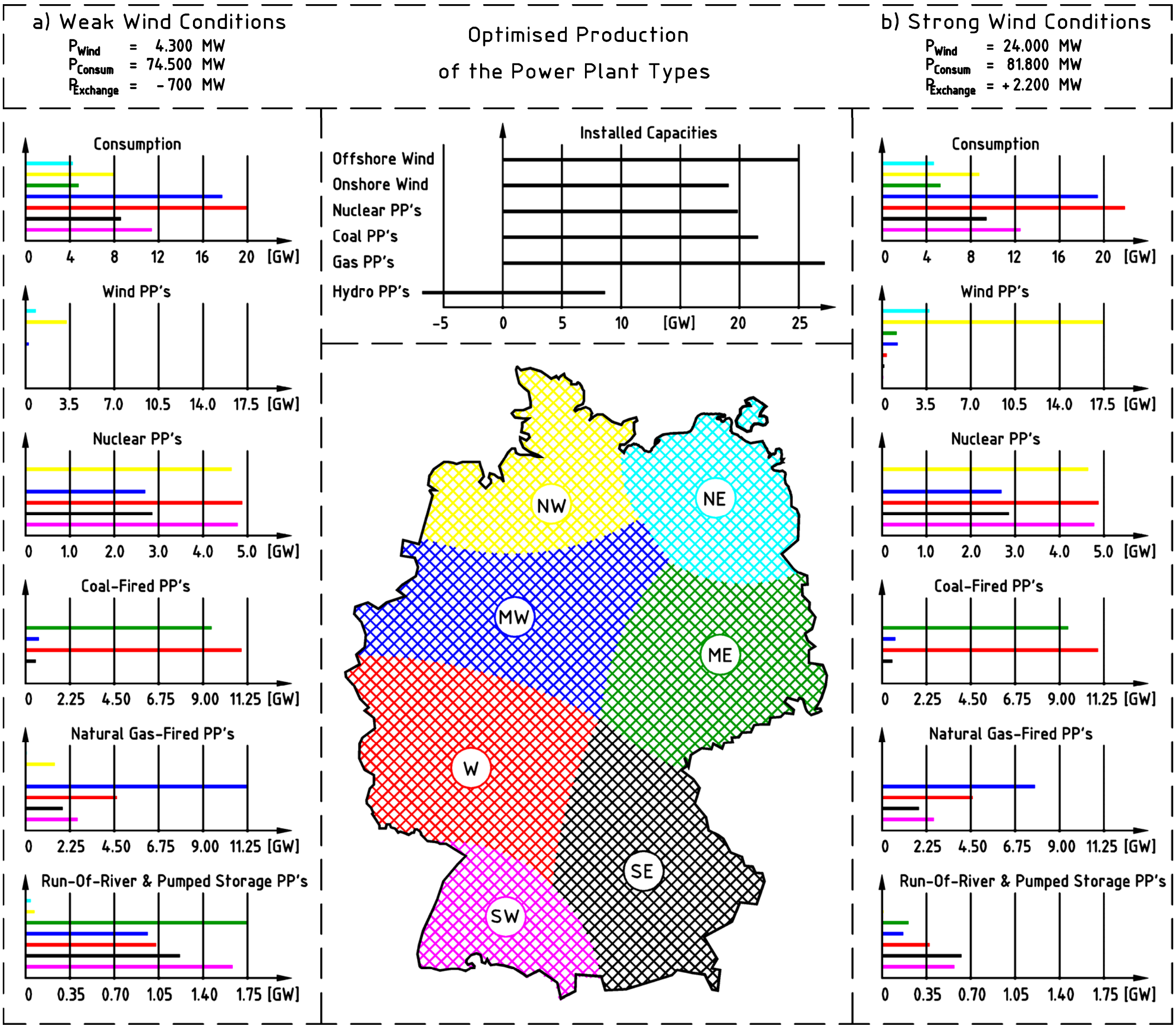

Fig. 4. Input and Output Data for the optimization

terms into 54 network nodes. In Fig. 3. the simplified model for optimization and network calculation is shown. The production and consumption of each UCTE member were summarized. Afterwards they were assigned to the main network nodes of the respective UCTE menbers. The transmission capacities between the European network operators were taken from the statistical yearbook of the UCTE. Thereby a calculation of the European power flow is possible in which the monthly changes are considered. This is particularly important since the German net is charged by power transits both to east-west direction and to north-south direction. Power exports in the winter and power imports in the summer are distinctive for Germany.

5. Optimization

The optimization of the model was carried out with a linear cost optimization. The investment costs are distributed over the economic life time of the power stations with the annuity method. The optimal power stations and transmission capacities as well as the optimal schedule of the power station park result from the optimization. However, the linear optimization is not able to consider the lower efficiencies in the operating mode with partial loads of the thermal power stations. The optimization was realized with the GAMS software package. The optimization was executed with the values of twelve randomly selected days in one year, one typical day for each month. It was calculated with a time resolution of one our. The result was projected onto the whole year with 8760 hours. This simplification was necessary because the available memory capacity of the computer was fully occupied. Additionally it was intended to reduce the computation time. Besides the parameters length and efficiency of the 380-kV transmission lines the costs for investments and maintenance were also implemented in the model. Parameters like efficiency, CO_2-emissions, fuel costs, investment costs as well as variable costs and operating costs, were assigned to the individual power station types. The calculation of the current-dependent CO_2-emission is based on the assumption that the coal-fired power stations will have an efficiency of 50 % in the year 2030 and the thermal emission factor will amount to 360 g CO_2/kWh. The gas-fired power stations will have an efficiency of 40 % in the year 2030 and the thermal emission factor of the natural gas will amount to 200 g CO_2/kWh.

6. Scenarios

The input and output data for the optimization for the main study cases are depicted in Fig. 4. The output data of the optimization are the input data for the network calculation in chapter 7. Three scenarios were defined and examined. First a scenario with wind power and with nuclear power, second a scenario with wind power and without nuclear power and third a scenario without wind power and with nuclear power. Fig. 5. gives an overview about the results of the optimization of all three scenarios.

6.1 Results of Scenario 1

The current demand of 579 TWh (included consumption and grid losses) will be met by coal-fired power stations at 31.0 %, by nuclear power stations at 29.8 %, by wind power plants at 21.0 %, by gas-fired power stations (CCCP's and gas-fired power stations) at 15.9 % and by hydroelectric power stations at 2.3 %. In detail hydroelectric power stations will provide a capacity of 8,500 MW and nuclear power stations will provide a capacity of 19,840 MW which were used as a constant value in the optimization. In addition coal-fired power stations will contribute a capacity of 21,550 MW, CCCP's will contribute a capacity of 27,170 MW and gas-fired power stations will have a capacity of 7,480 MW. Those three capacities were determined by the optimization. Taking this power station mix the current-dependent CO_2-emissions would amount to approx. 191 million tons per annum. The coal-fired power stations and nuclear power plants shall cover the base-load whereas the gas-fired power stations are designed for the peak-load. The then existing power supply system would not be sufficient to transport the energy which will be needed. As a further result the optimization inserted new transmission capacities in the net model. Bottlenecks will occur at the lines which go from the coastal area of the North Sea to the south. This is caused by the fact that the electricity generation centre will be then in the north part, especially in the Hamburg area and the consumption centres will be located in the west and south part (Rhine-Main and Ruhr district). The programme inserted transmission capacities of 7,800 MVA between the nodes Bremen and Muenster as well as capacities of 3,900 MVA between Kiel and Hamburg and 1,300 MVA between Essen and Muenster. The total length of the new transmission capacities would amount to approx. 1,200 km based on a 380-kV transmission line with a 1,300 MVA transfer capability.

6.2 Results of Scenario 2

The current demand of 577.6 TWh (included consumption and grid losses) will be met by coal-fired power stations at 32.7 %, by wind power plants at 21.0 %, by gas-fired power stations (CCCP's and gas-fired power stations) at 42.1 % and by hydroelectric power stations at 4.2 %. In detail hydroelectric power stations will provide a capacity of 8,500 MW which was used as a constant value in the optimization. In addition coal-fired power stations will contribute a capacity of 21,550 MW, CCCP's will contribute a capacity of 38,530 MW and gas-fired power stations will have a capacity of 7,.240 MW. Those three capacities were determined by the optimization. Taking this power station mix the current-dependent CO_2-emissions would amount to approx. 250 million tons per annum. The then existing power supply system would not be sufficient to transport the energy which will be needed. The programme inserted transmission capacities of 6,500 MVA between the nodes Bremen and Muenster as well as capacities of

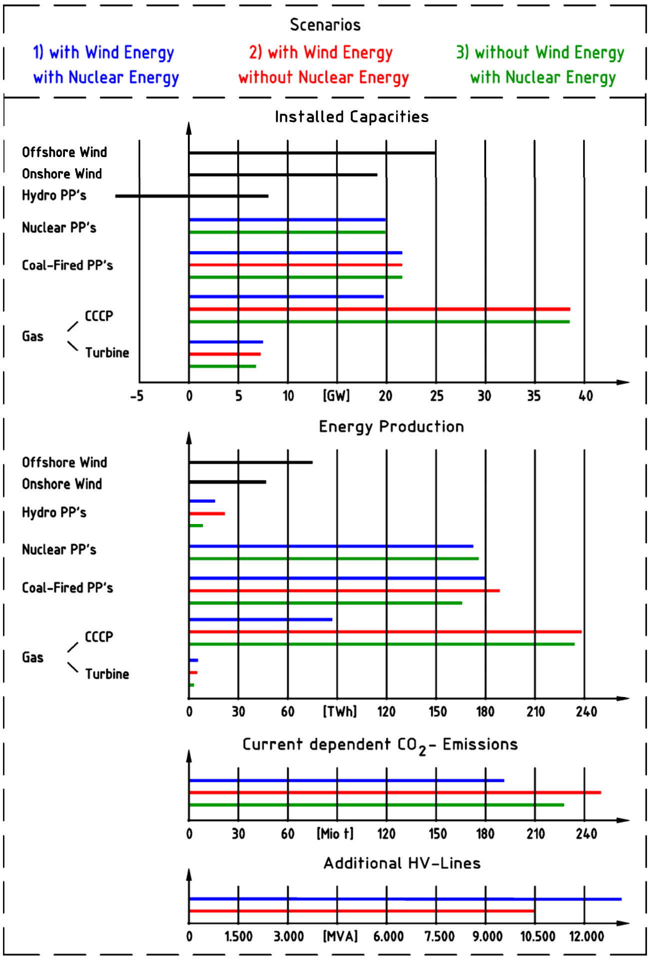

Fig. 5. Results of the optimization

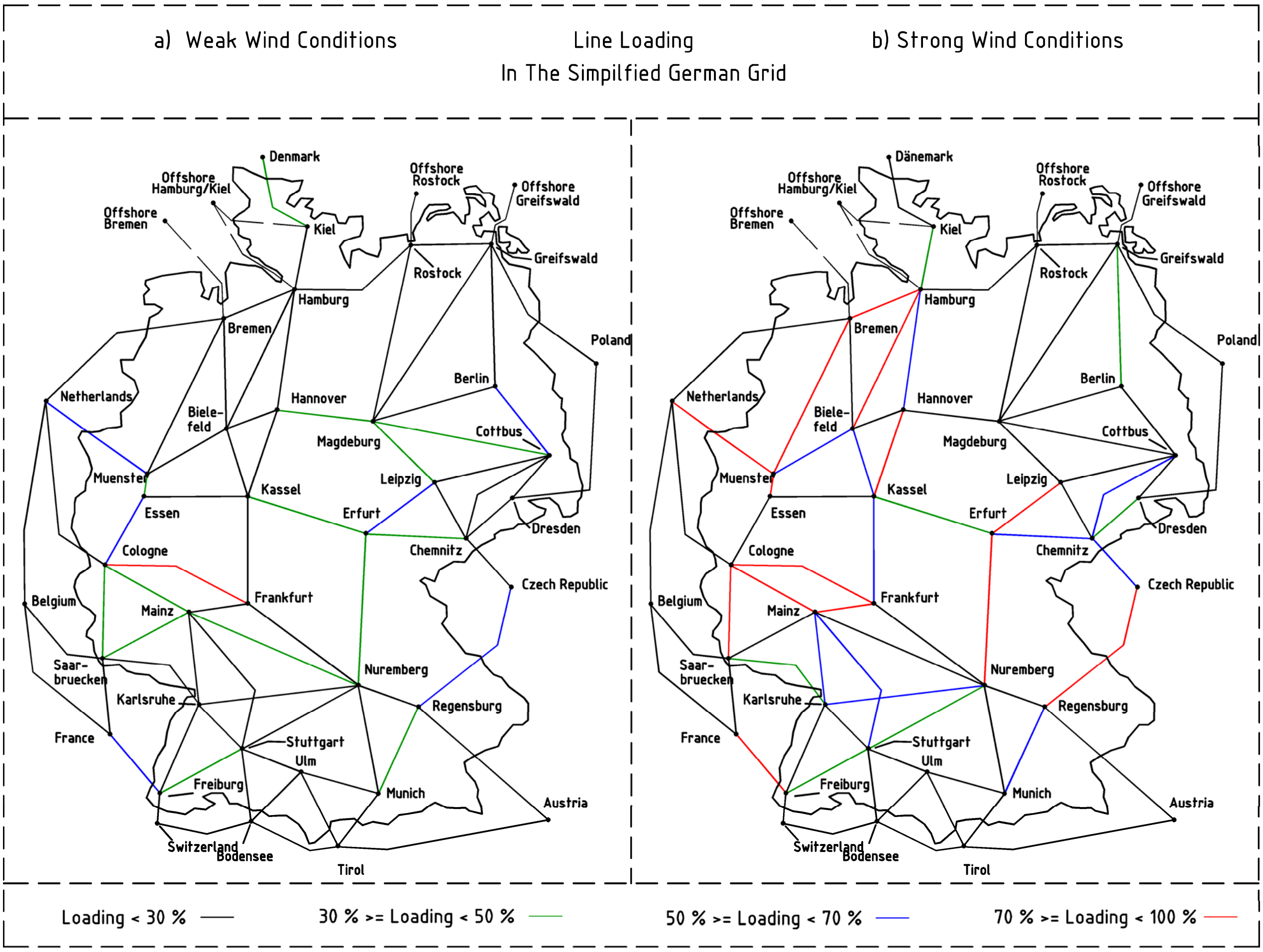

Fig. 6. Line Loading in the German Net

3,900 MVA between Kiel and Hamburg. The total length of the new transmission capacities would amount to approx. 800 km.

6.3 Results of Scenario 3

The current demand of 580.1 TWh (included consumption and grid losses) will be met by coal-fired power stations at 28.2 %, by nuclear power stations at 30.0 %, by gas-fired power stations (CCCP's and gas-fired power stations) at 40.4 % and by hydroelectric power stations at 1.4 %. In detail hydroelectric power stations will provide a capacity of 8,500 MW and nuclear power stations will provide a capacity of 19,840 MW which were used as a constant value in the optimization. In addition coal-fired power stations will contribute a capacity of 21,550 MW, CCCP's will contribute a capacity of 38,460 MW and gas-fired power stations will have a capacity of 6,680 MW. Those three capacities were determined by the optimization. Taking this power station mix the current-dependent CO_2-emissions would amount to approx. 225 million tons per annum. The then existing power supply system would be sufficient to transport the energy which will be needed. The optimization does not add any new transmission capacities.

7. Network Calculation

Various cases were investigated with the DIgSILENT software tool PowerFactory. The load flow investigation aims at the following:

- Up to which amount of wind energy feeding can the net be operated stably?
- Is the transmission grid able to transport several Giga Watts of wind energy through the net?

These questions shall be answered by load flow calculation with the simplified net model. A further shifting of the load flow in north-south direction as a consequence of the strong wind energy feeding in the northern part can be expected. The load flow shifting is depicted in Fig. 7. Because of the high feeding of wind energy from the North Sea the situation in the western part of the German grid system has to be judged considerably critically. The shifting of the power flow is carried out under the unavoidable demand on the net of the Benelux states as well as France and the Czech Republic. At increased feeding of wind energy to more than 20,000 MW the transmission lines are charged extremely and the voltage cannot be kept in its operating limits any more, see Fig. 6.

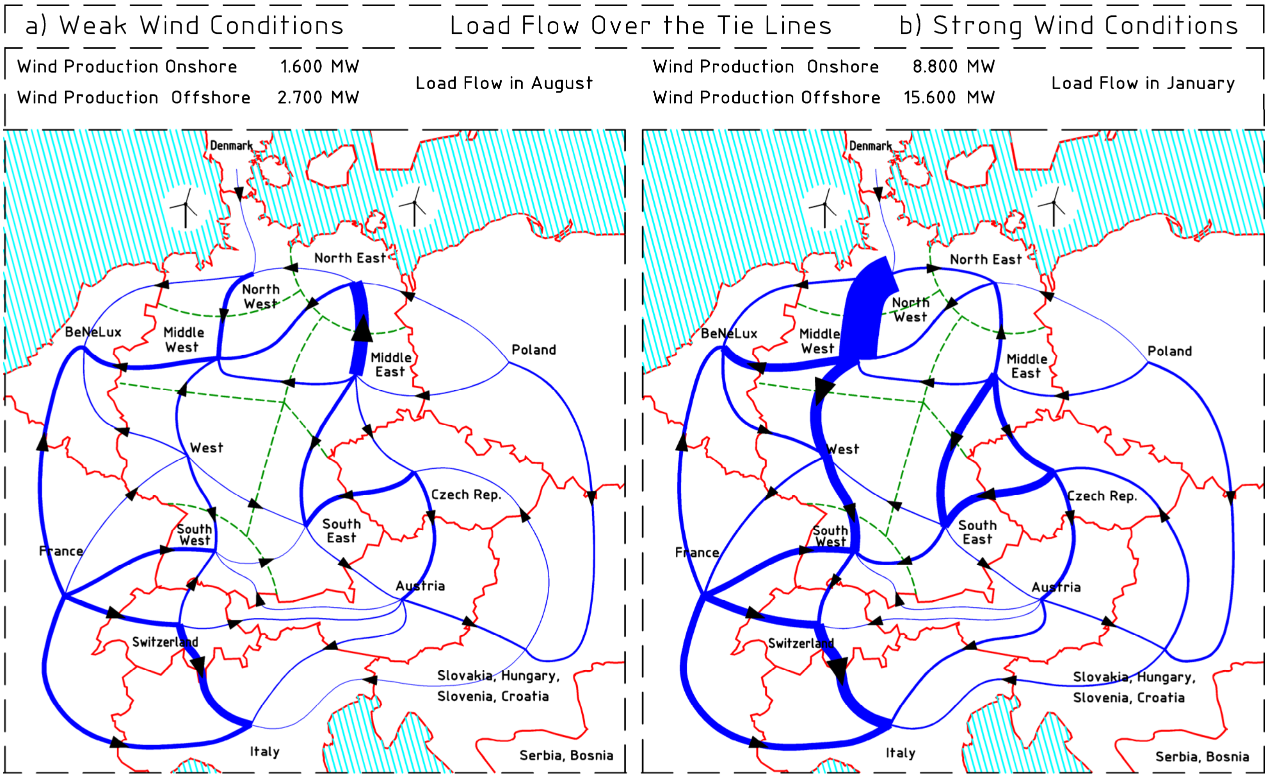

Fig. 7. Load Flow in the European Net

8. Conclusions

The German government plans a large extension of wind energy to 27.9 GW onshore and 26 GW offshore. Nevertheless it will hardly be possible to replace any thermal power plant capacity. However, it will be achievable to save fuel because the annual operation hours of the thermal power plants in full load operation will decrease. By way of saving fuel the CO_2-emissions are reduced automatically. But under partial load conditions the efficiency is lower so that the fuel saving effect is smaller than one might think. The greatest effect occurs if the future power station park consists mainly of wind energy plants, nuclear power plants und coal-fired power plants. Then the CO_2-emissions caused by current will amount to merely 191 million tons per annum. This indicates a significant reduction as compared to the year 2000. The power station park with low CO_2-emissions should be completed by modern combined cycle power plants. The coal-fired power stations are located inexpensively right next to the coal resources. The location of the nuclear power plants depends only on a sufficient supply of cooling water. The combined cycle power plants, which serve as backup power plants, can be built most efficiently in the western part of the German integrated grid near the large population centres. Bottlenecks arise especially at the lines between the northern and western part of the German grid. Because of the extension of the wind energy additional routes of about 1,200 km are needed in the high voltage level. These transmission lines have to be increased by a capacity of 13,000 MVA and the capacitive reactive power compensation at the bus bars has to be increased by 9,175 MVar. Then it will be possible to feed 24,000 MW of wind power in case of consumer full load and 17,000 MW of wind power in case of consumer partial load into the German grid. The switching off of wind parks in the North Sea (Giga Watt range) which is caused by storm or fault events can be compared to the switching off of several nuclear power plant blocks. If entire wind parks were switched off, the primary and secondary control with today's structure and dimension would reach their limits. Because of that in the future an improved and more efficient storage technology (hydrogen, more pumped-storage power plants) will be needed.

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