INFLUENCE OF WIND ENERGY ON THE POWER STATION PARK AND THE GRID

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Abstract: The energy supply in Germany was steered by the current demand of the consumers till now. It will change in an adjustment process to an energy supply led by stochastically arising energy offer by wind power stations. The development of the wind energy is pushed at suitable onshore and offshore sites. Up to the year 2030 onshore wind parks are expected with an installed power of approx. 22 GW and offshore wind parks with 26 GW installed power. The planned offshore wind parks with partly more Giga watts of power must be connected to the existing high-voltage transmission system. Another problem is that the wind energy is mostly produced in northern Germany, but is mainly needed in the middle and Southern part of Germany such as the Rhine-Main and Ruhr district. In order to compensate for the fluctuating feeding from the wind power stations backup power plants are needed. They must be able to provide reserve power. A simplified model of the German energy generation and transmission system was used for this investigation. Based on this model a conceivable scenario of the energy supply in Germany in the year 2030 will be discussed in this paper. *Copyright © 2006 IFAC*

Keywords: Renewable energy, bottlenecks, load management, congestion management, substitution of conventional power.

1. DEVELOPMENT OF THE OFFSHORE AND ONSHORE 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 renewable energy law (German abbreviation EEG) and the rapid technical development starting afterwards. By the end of 2003 wind power stations with an output of 14.315 MW were installed in Germany. By far the greatest shares hereof belonged to the energy supply companies of Vattenfall Europe (5.400 MW) and E.ON (6.250 MW). The German wind energy production amounted to approx. 18,6 TWh (E.ON 8,5 TWh and Vattenfall Europe 6,7 TWh) in the year 2003. 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 saturation will occur. By then 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 2030 an installed onshore wind power with approx. 22 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 18 wind parks which partly consist of several hundred single wind power plants. At present, wind parks are planned with an installed power of 21.561 MW in the North Sea and 4.437 MW in the Baltic Sea. Also, 800 MW shall be used for the production of hydrogen directly offshore. Figure 1 gives an overview over the historic and expected development of the German onshore and offshore wind energy capacity.

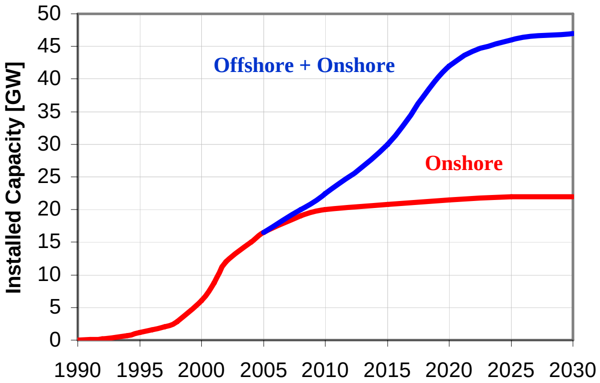


Fig. 1: Historic and expected development of the German onshore and offshore wind energy capacity

2. SUBJECT OF EXAMINATION

The challenge for the next years will be to develop a power station park which brings in line the different political interests and specifications, particularly the reduction of the greenhouse gases and the generation of electricity of local lignite and hard coal. With a model of the German energy generation and transmission system a scenario of the energy supply in the year 2030 with an installation of 26 GW offshore and 22 GW onshore wind power is analysed. The investigation is based on the conditions that the wind power plants will produce nothing but electrical power (no hydrogen) and there will be no further development of the pumped-storage power stations. The power station park and the transmission system should adapt optimally to the characteristics of the wind and ensure the balance between generation and consumption. Starting from these expectations the paper will address technical and economic problems related to the integration of 48 GW wind power into the German electricity grid. Basis of the analysis are two models: engineering and an economic model. The economic model is calibrated with the help of the engineering model. The analysis will be made on two levels:

1) An economic level, which will address the possible development of the costs of wind turbines and the costs related to the installation of extra transport capacities, increased demand of control power and back-up power. The conventional part of the power system will be described in two scenarios: A business as usual scenario, with a power plant structure which is similar to the current one and a wind scenario, in which the rest of the power system is more seen as a system to balance the stochastic power supply of the wind plants.

2) A technical level, which will address all questions related to the bottlenecks in the transport infrastructure. There are several results of the optimization in level 1. Firstly the capacities of base-load and peak-load power plants. Secondly the optimal behaviour of the power station park related to the influence of wind power. The transport capacities between the nodes in the grid are a further outcome of the model. These results of optimization are the input data for load flow calculation in level 2. The following questions shall be answered:

- 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 considerably reduction of the CO_2 emissions?
- At which sites in the transmission system can new power stations for lignite, hard 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?

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).

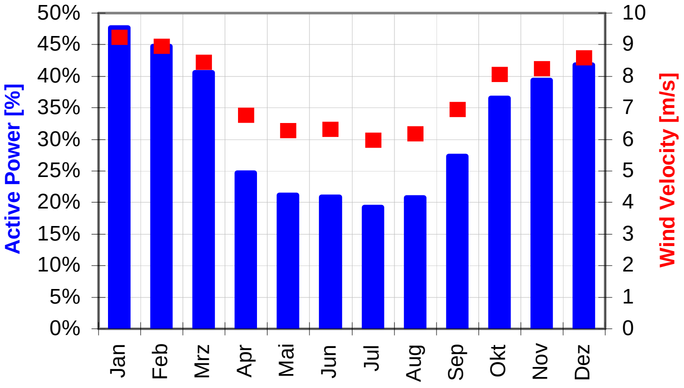


Fig. 2: Character of an offshore site in the North Sea

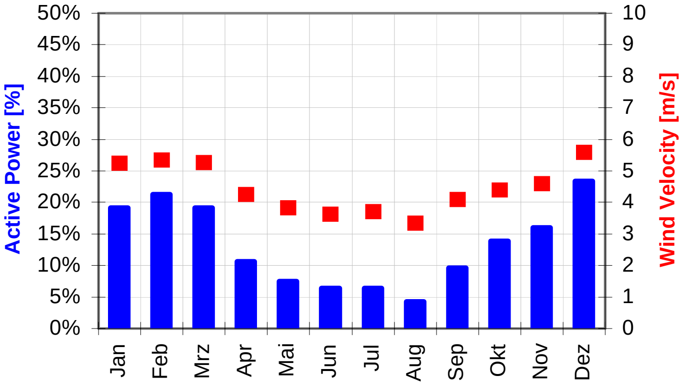


Fig. 3: Character of an onshore site in Southern Germany

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 the actual wind velocity. The wind velocity depends on the location and the actual meteorological situation, which itself depends strongly on the season. A comparison between two onshore sites in the North Sea and in Southern Germany is depicted in figures 2,3. The average wind velocities and the active power related to the installed nominal power are represented for a typical year. When comparing the figures 2 and 3 it is noticeable, that the average wind velocity in the North Sea is considerably greater then in Southern Germany. Due to the characteristics of the wind power plants ($P \sim v^3$) the active-power output is significantly smaller. This means, a profitable and economic wind energy production is possible only in the north part of Germany, especially offshore. On the other hand in Southern Germany this is hardly imaginable. The German Wind Energy Institute (DEWI) updates the details on the wind power installations for the single German federal states each month. 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

The transmission systems and the power station parks of the four big German energy supply companies were united, as there are EnBW, RWE, E.ON and Vattenfall Europe. 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 (lignite, hard coal, gas, pumped-storage, run-of-river). The nuclear power stations were replaced by lignite and hard coal power plants as well as natural gas fired power stations.

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 the year 2030.

The transmission capacities between the substitute 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 terms into ten network nodes. The production and consumption of each UCTE member were summarized in one network node. 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 (General Algebraic Modelling System) 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. In the future however these problems will be solved by way of better and faster algorithm of optimization. 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. The ratio of the electricity generation between lignite and hard coal amounts 45 % to 55 %. Due to this mixture the thermal emission factor results in 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. Two scenarios were defined and examined, scenario I (without wind power installation) and scenario II (with a sum of 48 GW wind power installation, onshore and offshore).

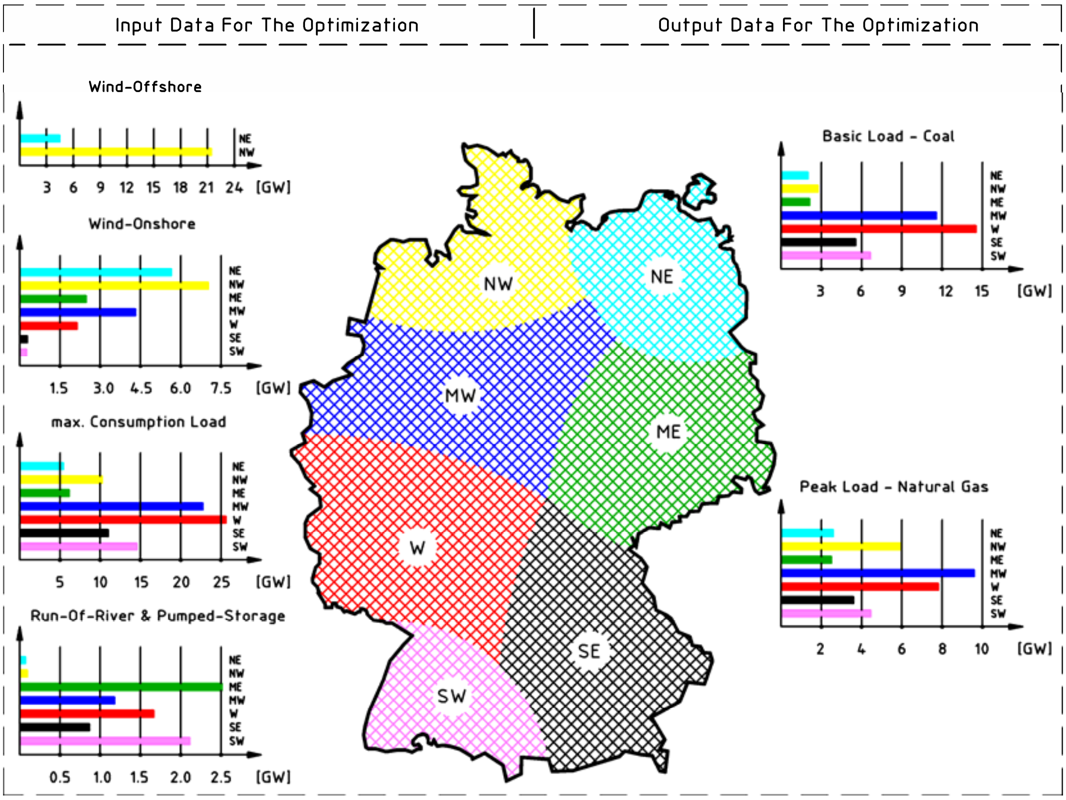


Fig. 4: Input and Output data for the optimization

6. SCENARIOS

6.1 Results of the optimization with a power station park without wind power (Scenario I)

The current demand of 571,2 TWh will be met by coal fired power stations at 84,7 %, by natural gas fired power stations at 13,1 % and by hydroelectric power stations at 2,2 %. 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 57.070 MW and natural gas fired power stations will have a capacity of 26.970 MW. Both capacities were determined by the optimization. The coal fired power stations shall cover the base-load whereas the gas fired power stations are designed for the peak-load. Taking this power station mix the current-dependent CO_2 emissions would amount to approx. 473,1 million tons per annum. The then existing power supply system would be sufficient to transport the energy which will be needed. As a further result the optimization does not add any new transmission capacities.

6.2 Results of the optimization with a power station park with wind power (Scenario II)

The current demand of 571,2 TWh will be met by wind power stations at 21,3 %, by coal fired power stations at 61,1 %, by natural gas fired power stations at 15,4 % and by hydroelectric power stations at 2,2 %. In detail wind power will provide a capacity of 48.000 MW and hydroelectric power stations will provide a capacity of 8.500 MW which both were used as constant values in the optimization. In addition coal fired power stations will contribute a capacity of 45.170 MW and natural gas fired power stations will have a capacity of 36.500 MW. Both capacities were determined by the optimization. The coal fired power stations shall cover the base-load whereas the gas fired power stations are designed for the peak-load. Taking this power station mix the current-dependent CO_2 emissions would amount to approx. 358,4 million tons per annum. The then existing power supply system would not be sufficient to transport the energy which will be needed. In the model a 2.600 MVA transmission line between Hamburg and Rostock which will be built until the year 2030 was assumed. 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. The 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 6.500 MVA between the nodes Bremen and Muenster as well as capacities of 5.200 MVA between Kiel and Hamburg. The total length of the new transmission capacities would amount to approx. 1.000 km based on a 380-kV transmission line with a 1.300 MVA transfer capability.

7. NETWORK CALCULATION

Various cases were investigated with the DIgSILENT software. Input quantities of the power flow calculation are the optimized power station capacities and line capacities from scenario II. For the whole German net the optimized power station capacities are represented in figure 4 which is subdivided into seven regions. The concentration of the wind power plants in the north is clearly

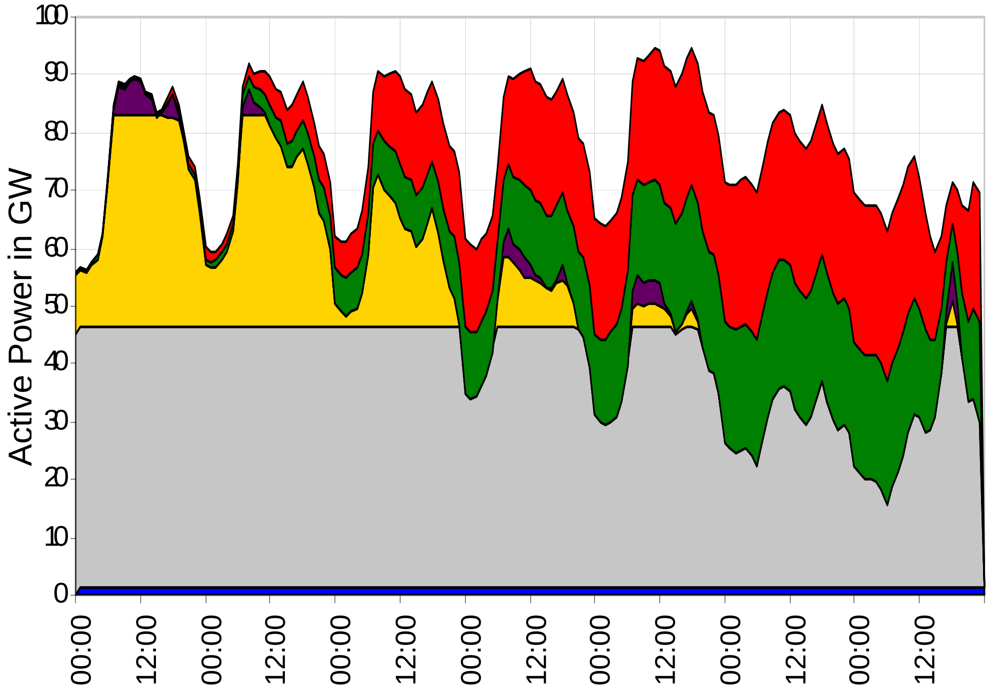


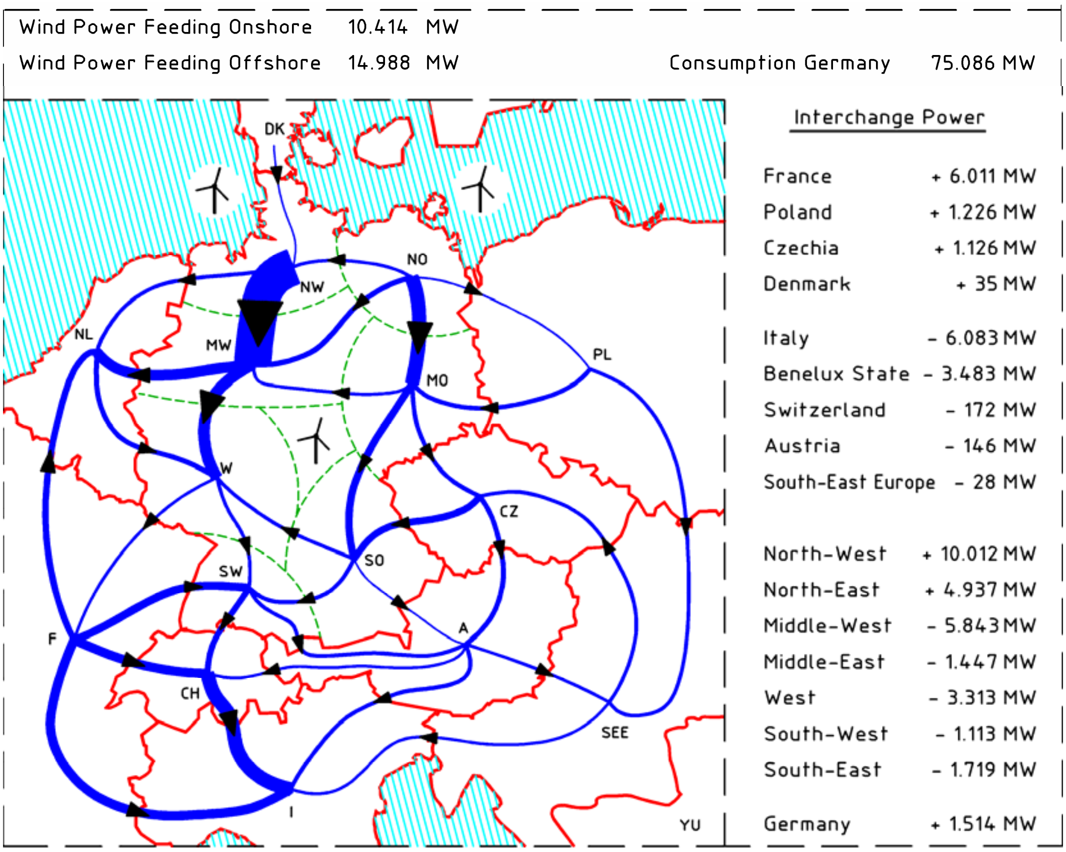
Fig. 5: Behaviour of the power station park during a week with strong wind power; grey (base load), yellow (peak-load), green (wind onshore), red (wind offshore), blue (run-of-river), purple (pumped-storage)

recognizable. This means that about 80% of the German wind energy would be produced in the north. It is also outstanding, that hardly any base-load power plants but considerably more peak-load power plants would be installed in the north. Hydroelectric power stations are only available in the southern regions due to the geographical conditions. The main consumer centres are in the western and southern part where, according to the consumer behaviour, more base-load and peak-load power stations would be installed. Furthermore the power stations where operated in a minimum-cost schedule.

In figure 5 a strong feeding from wind energy for the German net is represented for one week from Monday till Sunday. On Monday practically no wind feeding was offered. The figure shows the generation schedule as known so far. The schedule is designed for the hourly changing consumer power. The base-load power stations would cover the power up to approximately half of the expected peak-load. The peak-load power stations then would follow the consumers in their diurnal variation. The pumped-storage plants regulate the need for peak-load. With the feeding of wind energy increasing on Tuesday it was noticeable that at first the power of the pumped-storage plants and the peak-load power plants were throttled down. In the night from Wednesday to Thursday the power of the base-load power stations would have to be reduced, too. During the day on Friday very few peak-load power stations continue to feed energy into the net. The consumer demand then is covered only by the base-load power stations and the wind power stations. The pumped-storage plants regulate the need for peak-load. With the feeding of wind energy increasing on Tuesday it was noticeable that at first the power of the pumped-storage plants and the peak-load power plants was throttled down. In the night from Wednesday to Thursday the power of the base-load power stations would have to be reduced, too. During the day on Friday very few peak-load power stations continue to feed energy into the net. The consumer demand then is covered only by the base-load power stations and the wind power stations. During the weekend the consumer demand diminishes substantially. The wind feeding, however, remains constantly high. Further base-load power stations would have to be switched off after that. The generation schedule then would be dependent almost only on the feeding of wind energy. The consumer would play a completely subordinate role in this. 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 a rough estimation with the help of a simplified German network model. Figure 6 represents the active power load flow in the German as well as European net during the feeding of 25 GW wind power. A further shifting of the load flow in north-south direction as consequence can be clearly recognized. The width of the lines corresponds to the active power flowing over the tie lines. About 1/3 of the consumer load is covered by wind energy at this time. The situation in the western part of the German grid system which is characterized substantially by the high feeding of wind energy from the North Sea 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. This here represented 25 GW case is a theoretical borderline case. At increasing feeding of wind energy in this range the transmission lines are charged extremely and the voltage cannot be kept in its operating limits any more.



Wind Power Feeding Onshore 10.414 MW
Wind Power Feeding Offshore 14.988 MW
Consumption Germany 75.086 MW

Interchange Power

France	+ 6.011 MW
Poland	+ 1.226 MW
Czechia	+ 1.126 MW
Denmark	+ 35 MW
Italy	- 6.083 MW
Benelux State	- 3.483 MW
Switzerland	- 172 MW
Austria	- 146 MW
South-East Europe	- 28 MW
North-West	+ 10.012 MW
North-East	+ 4.937 MW
Middle-West	- 5.843 MW
Middle-East	- 1.447 MW
West	- 3.313 MW
South-West	- 1.113 MW
South-East	- 1.719 MW
Germany	+ 1.514 MW

Fig. 6: Load Flow situation by feeding of 25 GW wind power

8. CONCLUSIONS AND OUTLOOK

This paper was based on economic power plant models which have been provided with realistic parameters. In this study the minimal costs for the investments and for the operation of the German integrated grid for the year 2030 including the wind energy have been calculated with a linear minimum-cost model. Afterwards, the technical feasibility of the optimised power station park and of the optimised German grid was investigated by means of net calculation and simulation. At first it is obvious, that the installation of 22 GW onshore and 26 GW offshore wind energy does not lead to any significant reduction of the capacities of thermal power stations. The primary benefit of this heavy wind energy installation will be to save fuel, about 8,9 million of tons per annum of hard coal and about 18,2 million of tons per annum of lignite. But the operational availability of wind power generation is poor. Secondly a considerable number of new high voltage transmission lines will have to be built to transport the wind energy from the north part to the south and west parts of Germany. The used synthetic network model is sufficiently exact for the general estimation of the network extension. In the comparison with the dena-study similar results were obtained. By comparing the scenarios I and II in terms of the CO_2 emissions, then a reduction by approx. 114,7 million of tons will occur in scenario II. This value is still much higher than in the year 2000. In neither case there would be any reduction of the greenhouse gas emissions. Regarding the installed power station capacities one has to recognize that although fewer base-load power stations will have to be built (20,9 %) on the other hand more peak-load power stations will be needed (35,3 %) in scenario II. This seems logical since the wind can cover a certain base-load for a large area. Yet the considerable fluctuation of the wind can be compensated only with the fast natural gas fired power stations which then must be available in large numbers. However, seen absolutely the potential reduction amounts to only 2,8 % of conventional power station capacity (coal and gas) if 48 GW of wind power plants were installed. In principle, one can state as follows: If in Germany 22 GW Onshore and 26 GW offshore wind power capacity were installed, the CO_2 emissions on the side of the power stations could be kept approximately at today's level. Numerous technical and economic questions will have to be answered before there can be a considerable development of wind energy in Germany. Therefore further research and examinations are required in order to determine the necessary measures for the maintaining of today’s standards as regards supply reliability.

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