ANALYSIS OF THE IMPACT OF RENEWABLE ELECTRICITY GENERATION ON CO_2 EMISSIONS AND POWER PLANT OPERATION IN GERMANY

Frank Sensfuß, Massimo Genoese, Mario Ragwitz

Fraunhofer Institute for Systems and Innovation Research, Breslauer Straße 48, 75139 Karlsruhe, 0721-6809-133, Frank.Sensfuss@isi.fraunhofer.de, www.isi.fhg.de

Abstract: Renewable electricity generation plays an important role in the German strategy to reduce CO_2 emissions. This paper seeks to analyse the impact of renewable electricity generation on the CO_2 emissions and utilisation of the power plant portfolio in Germany. The analysis based on the PowerACE simulation platform shows that most of the renewable electricity generation replaces hard coal fired power plants.

Keywords: Renewable electricity generation, electricity market, CO_2 emissions, power plant operation

1 Introduction

The support of renewable electricity generation is an important part of the German strategy to reduce CO_2 emissions. In Germany the government began stimulating the market penetration of renewable electricity generation in the 1990s. After a period of support consisting mainly of research and development programmes, fixed feed-in tariffs were introduced in 1990. Despite several modifications, the principal system of feed-in tariffs has been in place for more than 15 years in Germany. In combination with additional support schemes such as soft loans with reduced interest rates, the German support policy has led to a remarkable growth in renewable electricity generation. In 1990, most of the renewable electricity generation was based on large hydropower plants. The electricity generation by other technologies such as wind, photovoltaic and biomass was less than 0.3 TWh. (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2006). As a consequence of the continuous support, electricity generation from new renewable energy sources reached more than 52 TWh in 2006 (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit [BMU], 2007). The most important technology within this development is electricity generation from wind energy which attained an exponential growth from an installed capacity of 56 MW in 1990 to 20622 MW (Deutsches Windenergie Institut [DEWI], 2007) by the end of 2006. The considerable capacity and the fluctuating character of electricity generation by wind have triggered a debate on the effect of wind power on the electricity sector. Since renewable electricity generation plays an important role in the strategy to reduce CO_2 emissions it is important to assess the CO_2 savings created by renewable electricity generation. This paper seeks to analyse the impact of the supported renewable electricity generation on the CO_2 emissions and utilisation of the conventional power plant portfolio.

2 Methodology

An important aspect of the German feed-in support is the fact that renewable electricity generation has privileged access to the electricity grid. The renewable generation has to be bought by the grid operators in advance. As this electricity is passed on to the consumers it reduces the electricity demand that has to be covered by conventional power plants. In the short run, this effect reduces the utilisation of conventional power plants. The reduction of the load that has to be covered by conventional power plants reduces the utilisation of the existing plants. Due to the lower utilisation of the conventional power plants the CO_2 emissions of the power plant portfolio are also reduced. However, the actual impact of the renewable electricity generation on the utilisation of each power plant depends on its position within the merit-order curve which sorts power plants according to their variable cost. Depending on the load and the amount of renewable electricity generation the different plant types are affected by renewable electricity generation. This situation is illustrated in Figure 1.

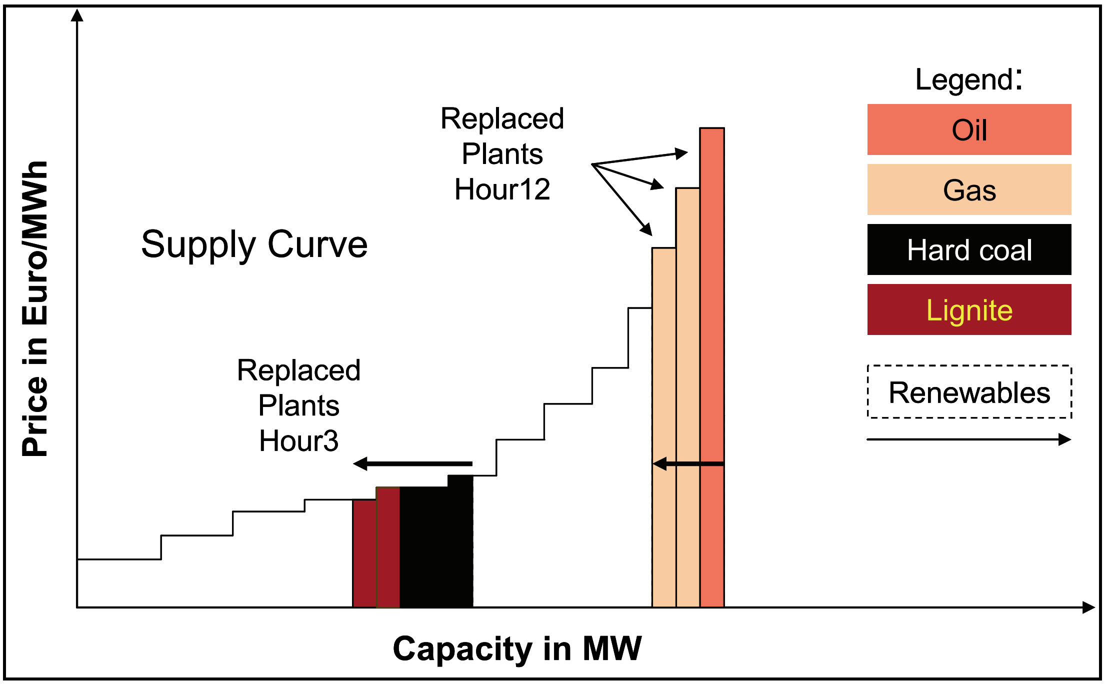

Figure 1 Impact of renewable electricity generation in different hours

In times of high demand renewable electricity generation replaces the most expensive peak power plants which are mostly gas and oil fired. In times of low demand renewable electricity generation replaces hard coal and lignite fired plants. Since the different plant types are characterized by considerable differences in their CO_2 emissions a crucial aspect for the analysis of the CO_2 savings is to determine which power plants are replaced by renewable electricity generation. An overview of the emission factors of selected plants is given in Table 1. Lignite power plants with a low efficiency are characterized by the highest CO_2 emissions of ca. 1200 g/kWh while efficient gas combined cycle power plants reach specific CO_2 emission of ca. 350 g/kWh.

Table 1 CO_2 Emission factors of selected power plant types

Fuel	Efficiency %	Specific Emissions g/kWh
Lignite	33	1202
Lignite	42	945
Hard coal	33	1018
Hard coal	43	781
Gas	30	668
Gas	58	346

Source (own calculations)

In the given context it is important to note that electricity demand and renewable electricity generation vary on hourly level. As a consequence the power plants which are affected by renewable electricity generation vary on the same time scale. A comparison of a selected day in October 2006 is given in Figure 2. The figure shows the impact of renewable electricity generation supported by the EEG on the remaining system load that has to be covered by conventional power plants. The load of renewable electricity generation in the selected period varies between 4.4 GW and 14.7 GW.

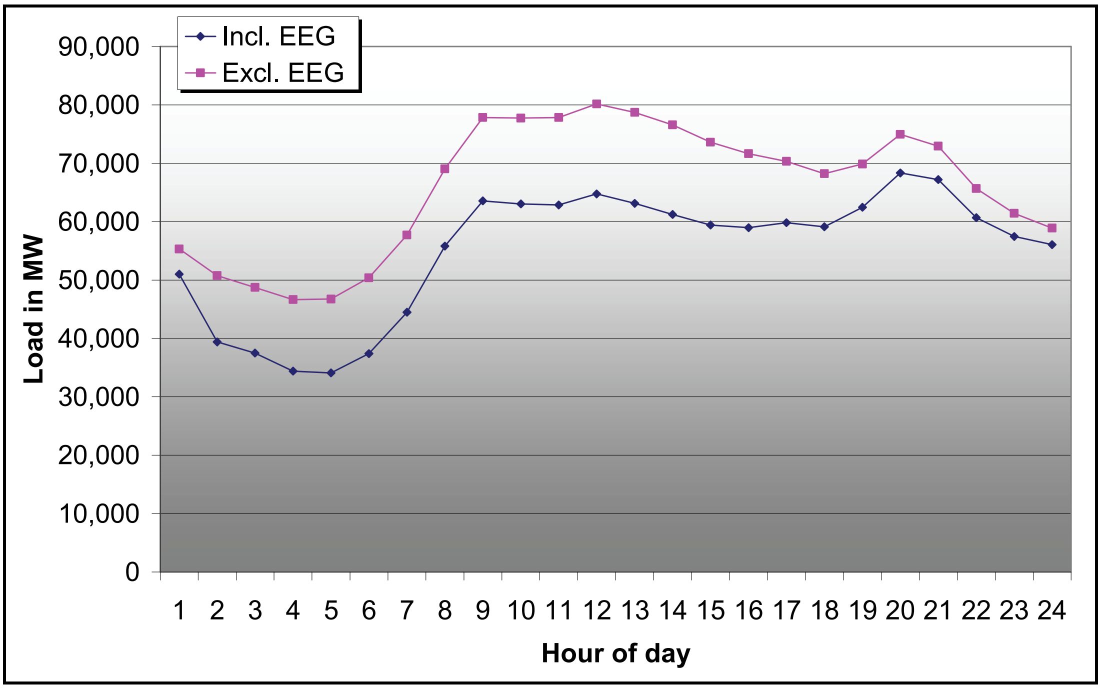

Figure 2 The impact of renewable electricity generation on the remaining system load (day in 2006)

In the long run the reduced utilisation of the different conventional power plants will also affect investment decisions leading to a long run impact on the CO_2 emissions of the power plant portfolio. However this paper focuses on the short run impact of renewable electricity generation on the power plant portfolio. The fact that the situation changes on hourly level underlines that a computer model is needed in order to analyse this issue for an entire year. Therefore the analysis is carried with the detailed electricity market simulation platform

PowerACE able to simulate hourly spot market prices (Sensfuß, 2007,Genoese et al., 2007). The PowerACE simulation platform simulates important players within the electricity sector as computational agents. Among these are agents representing consumers, utilities, renewable agents, grid operators, government agents and market operators. An overview of the developed simulation platform is given in Figure 3.

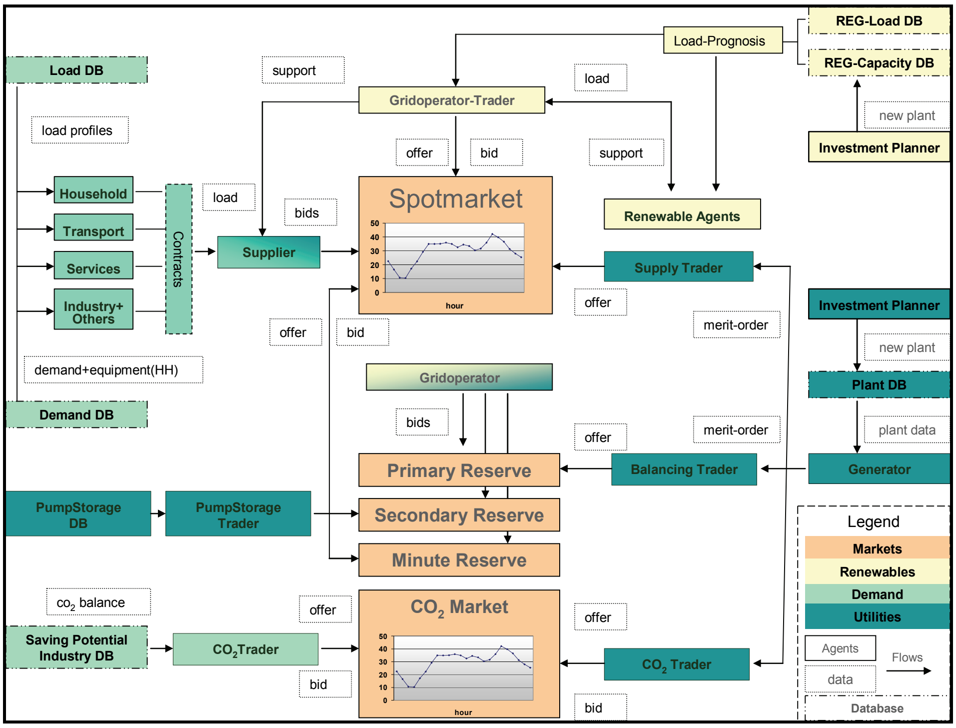

Figure 3 Structure of the PowerACE simulation platform

Source: own illustration

In order be able to generate realistic results a special emphasis is given to the integration of detailed data on power plants, load and renewable electricity generation. The model simulates reserve markets and the spot market. Spot market prices are calculated on hourly level for an entire year. Based on a price prognosis power plants and pump storage plants are bid into reserve markets and the spot market. For the given simulation the bid price for power plants is based on variable cost and start up cost. The calculation of the bid price is presented in Formula 1. Power plant outages are simulated by a random generator. Exports and imports of electricity are integrated based on static profiles calculated by the PERSEUS linear optimization model (Möst et al., 2005, Enzensberger, 2003), a European energy system model where Germany and all border countries are modelled. In view of the transmission capacities, costs, electricity demand and supply, export/import flows between these countries are computed and used as a fixed load flow for the PowerACE model runs. Demand and renewable load are bid with price inelastic bids into the market. In a first step the model is run 50 times with renewable electricity generation and an average hourly price series, the utilisation of power plants and the CO_2 emissions is calculated. In a next step the procedure is repeated and the supported renewable electricity generation is switched off. The differences of both time series are analysed.

Formula 1Calculation of the bid price for power plants

$$p_{i,h} = \begin{cases} max(\frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i - \frac{s_i}{\upsilon}, 0) & if\ \varphi_h < \left(\frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i\right)\ and\ i \in G \\ \frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i + \frac{s_i}{\sigma} & if\ \varphi_h > \left(\frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i\right)\ and\ i \in P \\ \frac{p_{f,i}}{\eta_i} + \frac{z \cdot e_f \cdot \zeta_f}{\eta_i} + o_i & otherwise \end{cases}$$

$$i \in M;\ G \subset M;\ P \subset M;\ G \cap P = \emptyset$$

Legend:

Variables			Unit	Indices		
e	=	CO_2-emission factor	[t CO_2/MWh]	f	=	Fuel
G	=	Set of base load power plants	[None]	h	=	Hour
M	=	Set of all operation-ready power plants	[None]	i	=	Plant
o	=	Variable operation and maintenance cost	[Euro/MWh]			
P	=	Set of peak load power plants	[None]			
p	=	Price	[Euro/MWh]			
s	=	Start-up cost of plant	[Euro]			
z	=	CO_2 price	[Euro/t]			
η	=	Efficiency	[%]			
σ	=	Number of scheduled hours per day	[Hour]			
υ	=	Number of unscheduled hours per day	[Hour]			
φ	=	Predicted price of spot market	[Euro/MWh]			
ζ	=	CO_2 price integration factor	[None]			

3 Results

In order to determine the impact of renewable electricity generation on the CO_2 emissions in the German electricity sector the calibrated model is used to simulate the electricity market for the years 2004, 2005, and 2006. 50 simulations are carried out for each year. The model calculates the CO_2 emissions of each running power plant according to Formula 2:

Formula 2: Calculation of the annual CO_2 emissions in PowerACE

$$\alpha = \sum_h \sum_i \frac{v_{i,h} \cdot e_f}{\eta_i};$$

Legend:

Variables			Unit	Indices		
e	=	CO_2-emission factor	[t CO_2/MWh]	f	=	Fuel
v	=	Hourly electricity generation of plant	[MWh]	h	=	Hour
α	=	Annual CO_2 emissions	[t]	i	=	Plant
η	=	Efficiency	[%]			

The resulting time series is calculated as average of the simulation runs in order to level out variations caused by the random variables used to simulate power plant outages. In a second step the same procedure is applied to 50 simulation runs without renewable electricity production supported by the feed-in tariff. Since the development of large hydro plants has not yet been affected by the renewable support scheme, electricity production of large hydro plants is taken into account in both simulation settings. The resulting CO_2 emissions are compared for both time series. An overview of the simulation results is given in Figure 4. Since PowerACE does not account for the additional CO_2 emissions caused by partial load operation of conventional power plants due to renewable electricity generation an adjustment of the results is necessary. Based on an existing review of different approaches to the calculation of CO_2 savings (Klobasa, Ragwitz, 2005), a reduction factor of 10 % is assumed which is the highest value of the compared studies. The results of the corrected CO_2 savings are presented in Table 2.

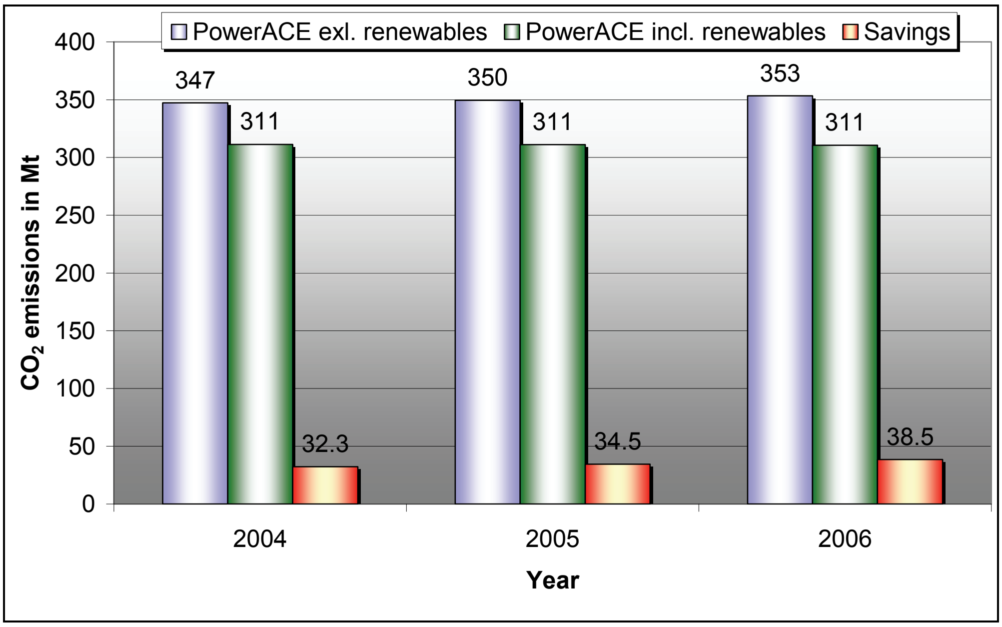

Figure 4 Simulated annual CO_2 emissions of the German electricity sector
Source: own illustration

Table 2: Corrected CO_2 savings by renewable electricity generation

Category	Year	Excl. EEG	Incl. EEG	Difference	Partial load reduction	Corrected savings	Renewable Generation	Specific savings
		Mt	Mt	Mt	%	Mt	TWh	kg/MWh
CO_2 emissions	2004	347.2	311.3	35.9	10	**32.3**	41.5	778
CO_2 emissions	2005	349.5	311.2	38.3	10	**34.5**	45.5	758
CO_2 emissions	2006	353.4	310.6	42.8	10	**38.5**	52.2	738

Although PowerACE allows for the calculation of CO_2 savings on a very high detail level, it seems to be important to compare the results of the calculated CO_2 savings with the literature in order to evaluate the results. Klobasa and Ragwitz (Klobasa, Ragwitz, 2005) provide an overview of existing studies and provide an own estimation of the CO_2 savings in the year 2003. An overview of some studies presented in the review by Klobasa and Ragwitz is given in Table 3. The results show that the calculated CO_2 savings are higher in the selected literature. Thereby it has to be taken into account that all the studies deal with the period before the introduction of the European emission trading system which has changed the merit-order curve of power plants. An additional aspect is the higher renewable electricity generation in the year 2005 and 2006 which can lead to the replacement of less CO_2 intensive plants. Based on this comparison it can be stated that the CO_2 savings calculated within this paper represent a conservative calculation of the CO_2 savings by renewable electricity generation.

Table 3: Selected studies on CO_2 savings of renewable electricity generation

	Klobasa and Ragwitz (2005)	**Klobasa and Ragwitz (2005)**	**Sontow, 2000**	**Geiger et al., 2004**
Year	2003	2003	Before 2000	Plant portfolio 2000,
Technology	Renewables incl. large hydro	Savings excl. hydro	Wind	Wind (15 GW)
Savings	943 kg/MWh	875 kg/MWh	800 kg/MWh	828 kg/MWh

Source: All values are taken from the overview given in (Klobasa, Ragwitz, 2005)

A more detailed analysis shows which power plants are replaced by renewable electricity generation. The results are presented in Figure 5. The simulation results for the year 2006 show that most of the electricity generation that is replaced by renewable electricity generation is based on hard coal power plants. The share of hard coal in the replaced electricity production is 62%. Gas fired power plants account for 26% of the replaced electricity generation. Lignite power plants account only for 11% of the replaced renewable electricity generation. This can be explained by the fact that lignite power plants are at the lower end of the merit-order curve. Therefore lignite power plants are rarely replaced by renewable electricity generation in the analysed year. Nuclear power plants are almost unaffected by renewable electricity generation since they are at the very low end of the merit-order curve. Oil fired power plants are affected by renewable electricity generation but as their overall importance in terms of produced electricity is very low only 1% of the electricity production of conventional power plants replaced by renewable electricity generation is based on oil fired power plants.

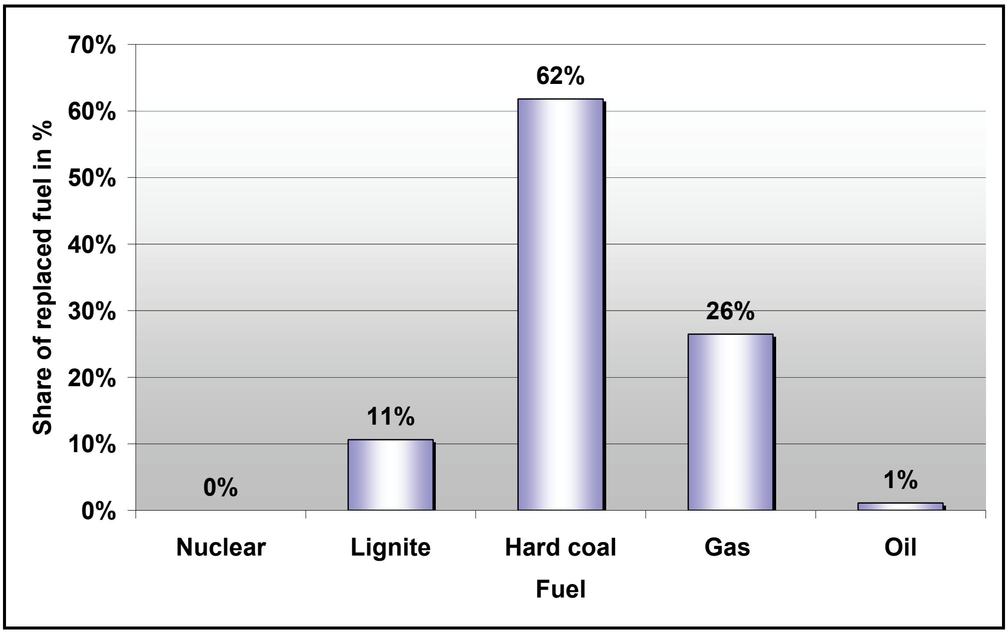

Figure 5 Share of fuels replaced by renewable electricity generation

A more detailed analysis for the case of hard coal fired power plants shows the impact of efficiency on the utilisation of power plants. Figure 6 shows the comparison of the utilisation of hard coal fired power plants with different efficiencies and the impact of renewable electricity generation. The picture shows that the efficiency of a hard coal power plant has a considerable impact on the utilisation of the power plant. While the most efficient hard coal fired power plants reach an utilisation between 7000 and 8000 full load hours the least efficient hard coal fired power plants reach an utilisation below 2000 hours.

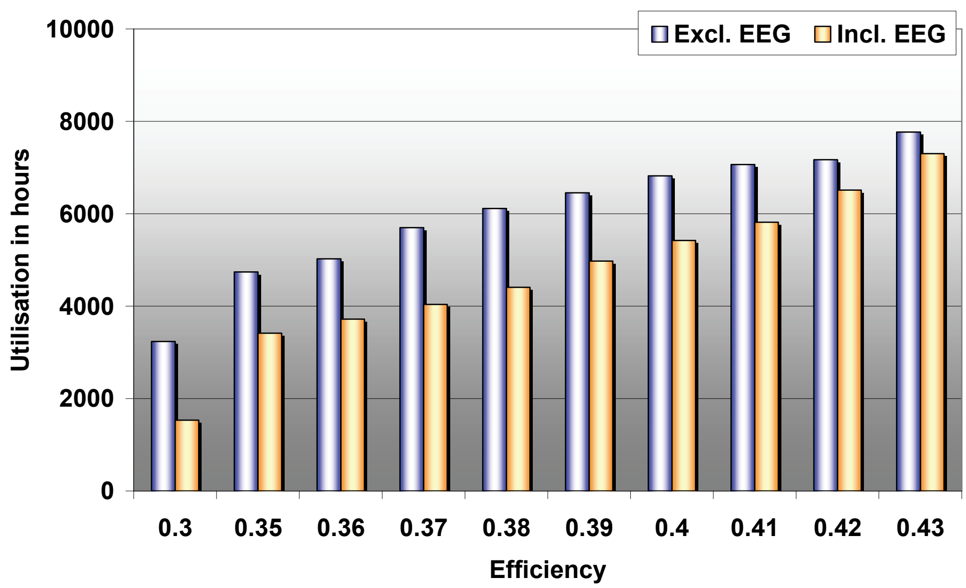

Figure 6 Simulated utilisation of hard coal fired plants
Source: own illustration

The results indicate that there is a tendency showing that less efficient plants are also more heavily affected by renewable electricity generation since they have a higher position in the merit-order curve. The utilisation of the most efficient plants is reduced by 6% or 470 full load hours. With decreasing efficiency the lost utilisation increases to 53% or ca. 1700 full load hours for the least efficient hard coal power plants.

4 Conclusions

This paper analyses the impact of the supported renewable electricity generation on CO_2 emissions on power plant operation in Germany. The analysis is carried out based on the detailed electricity market simulation platform called PowerACE. The analysis is carried out for the years 2004-2006. Since the simulation platform is not yet capable to integrate the additional CO_2 emissions caused by partial load operation the results have to be adjusted based on literature values. The analysis shows CO_2 savings between ca. 780 and 740 g/kWh. The total volume of the CO_2 savings of 38.5 Mt underlines the importance of renewable electricity generation for the reduction of green house gas emissions in Germany. A detailed analysis on power plant level for the year 2006 shows that most of the renewable electricity generation replaces hard coal fired plants (62%). Gas and lignite power plants account for a share of 26% and 11%. An additional analysis within the category of hard coal fired power plants shows that less efficient power plants are more affected by renewable electricity generation which can explained by their higher position within the merit-order curve leading to a higher probability to be replaced by renewable electricity generation.

Although the impact of renewable electricity generation on CO_2 emissions in Germany has already been analysed in previous publications (e.g. Klobasa and Ragwitz, 2005) this paper may provide a valuable contribution to this discussion due to the extension of the analysis into the period after the introduction of the European Emission Trading scheme (2005-2006). Another contribution is the application of a very detailed simulation platform based on a realistic fundamental dataset which allows for an analysis on hourly level for an entire year.

A promising extension of the developed simulation platform could be the integration of partial load operation of power plants into the simulation. This extension could provide an even more detailed picture of the impact of renewable electricity generation on the conventional power plant portfolio.

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