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Modernisation of existing and new construction of power plants in Germany: results of an optimisation model

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Abstract

If the average lifetime of a power plant is assumed, as is commonly accepted, to be 30 to 35 years, then the German power plant inventory is outdated. In light of this, several studies have predicted a comprehensive conversion of the German power-generating industry within the next few years. It is the objective of this paper to verify this finding using an optimisation approach. Different policy scenarios are defined. The requirements are calculated for the future modernisation of existing and the new construction of conventional power plants in Germany, as well as the share of new and total capacity provided by various energy sources. The optimisation approach used considers the modernisation of old plants as an investment alternative to the construction of new plants. This fills the gap in existing power station models which do not consider plant modernisation. Estimates, depending on scenario assumptions, show that discrepancies between models that include plant modernisation and models that do not include it are considerable.

Keywords: New power plant construction; Old plant modernisation; Mixed integer linear programming

1. Introduction

There are several approaches which assess the future requirement for new power generation capacity in Germany (e.g., Enquete Commission, 2002; UBA, 2003;

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Markewitz and Vögele, 2003). All these studies follow a very simple procedure: In the first stage, the future total requirement for power generation capacity is assessed. Then, assuming a fixed technical lifetime (usually 30 to 35 years, sometimes different for the single power plant types), the dimension of retired old capacity is calculated. Finally, the requirement for new power generation capacity is assessed by subtracting the (still existing) old capacity from future total requirement.

The differences in the results of existing studies are due to different assumptions about future total requirements for power generation capacity and about the rate at which existing plants are retired. The current UBA paper (2003) predicts a decline in total net power generation capacity from about 110 at present to 70 GW_{el} in the year 2020, while the Enquete Commission (2002) and Markewitz and Vögele (2003) assume an almost unchanged total net power generation capacity for 2020. The UBA paper (2003) estimates that the net power generation capacity of old plants at 30 GW_{el} for the year 2020; the Enquete Commission (2002) assume a figure of 40; and Markewitz and Vögele (2003) estimate the figure at 50 GW_{el} for the year 2020 in their base scenario. Thus, the cumulative requirement for new net power generation capacity up until the year 2020 is 40, 70, and 60 GW_{el}, respectively.

The average age of a conventional power plant in Germany is estimated at 22 years based on the author's own calculations. Given that the expected lifetime of such a plant is 30 to 35 years, the German power plant inventory is clearly outdated. This is why all three studies expect a similarly great share (60% to 70%) of newly built power plants in the total net power generation capacity in the year 2020. The next few years will, therefore, be decisive for the ecological and economical conversion of the German power-generating industry.

In contrast to existing studies, this paper uses an optimisation model for the calculation of the requirement for new power generation capacity in Germany. At the same time, the optimisation model is used for the estimation of modernisation requirement for existing power plants and for the assessment of the share of new and total capacity provided by various energy sources. The estimations presented in this study are focused on conventional power generation. This should be borne in mind when the magnitude of requirement for new capacity presented in this paper is compared with the magnitude presented in the studies mentioned above. They consider, after all, new capacity both in conventional and nonconventional, such as wind-based, power generation.

The optimisation approach used considers the modernisation of old plants as an investment alternative to the construction of new plants. This is an improvement on existing power station models such as those of Hoster (1996) or Vögele (2001). A consideration of plant modernisation is necessary because plant modernisation leads, or indeed should lead to an extension of the economic lifetime of old plants (cp. Melchior, 2003) which then has implications for the requirement for new plants.

Using an optimisation model to assess the requirement for new power generation capacity is very different from the method upon which the existing studies mentioned above are based. While existing studies explain the retirement of old plants statistically (Enquete Commission, 2002; UBA, 2003) or technically, due to abrasion (Markewitz and Vögele, 2003), the optimisation approach explains the retirement economically. If the specific total costs of new power stations are lower than the specific reversible costs of old plants, the old plants are considered no longer competitive and are retired. This means that, in addition to future total requirement for power generation capacity, assumption for fuel and maintenance costs or political parameters, such as the implementation of CO_2 allowances, influences the requirement for new plants.

This paper is organised as follows: The model choice is explained in Section 2. The underlying assumptions of the optimisation model are clarified in Section 3. In Section 4, the model itself is presented. Scenario design and model parameters follow in Section 5. Model results are discussed in Section 6. Section 7 shows the discrepancies between those power station models which consider and those which do not consider plant modernisation. In Section 8, results are summarised and a perspective on future workings is given.

The source code of the model can be found at http://www.phil.uni-erlangen.de/economics/get.php?page=mitarbeiter/schwarz/powerplantmodel.gms.

2. Model choice

It is the objective of this paper to assess the requirements for future modernisation of existing and new construction of conventional power plants. This necessitates the development of a technology-based model of the electricity market which considers modernisation of old plants as an investment alternative to the construction of new plants. These power plant models are usually formulated as linear programs (see, for example, the approaches of Hoster, 1996; Vögele, 2001; Peek et al., 2004). Linear approximation of (at least) the (variable) costs of a power plant is unproblematic (see Pfaffenberger, 1993), and efficient algorithms to solve even comparatively large linear programs exist. This is important for power plant models. The necessity to consider a multitude of time periods, load segments, modernisation, and new building options, as well as sometimes regions, leads, in most cases, to comparatively large optimization problems.

The model developed here is formulated as a mixed integer linear program, a variety of linear programming which is often used in mineral (see, for example, the approaches of Brown et al., 1983; Dammert and Palaniappan, 1985), but also sometimes in electricity market modelling (Nollen, 2003). Its advantage is that production and transport quantities are continuous (and positive) variables. In addition, the mixed integer linear programming models are based on binary variables which are associated with production capacities. This, as opposed to linear programming, ensures that only whole plants and not, for example, half a plant can be built, modernised, or deconstructed. Moreover, fixed costs of production can now be linked to capacities. In linear programming models, these have to be connected with production quantities although fixed costs are defined as costs relevant independent of production.

3. Model assumptions

The proposed model assumes perfect competition and therefore price-taking behaviour for suppliers, who are in this case the operators of conventional power plants. It is a multiperiods approach. As is common for partial equilibrium models with given demand (in this case: for electricity of different load segments), total discounted costs (TC) of production (in this case: of power generation) are minimised under several constraints (see, for example, Labys and Pollak, 1984; Labys, 1999). The innovative element is that the modernisation of existing plants and construction of new plants are modelled as alternative investment options. Fig. 1 gives an overview of symbols used. The model assumptions are:

3.1. Time periods

Several production periods, represented by t, are assumed; $t \in \{1, 2, \ldots, T\}$. In addition, a Greenfield investment period, represented by τi, is considered; $\tau i \in \{1, 2, \ldots, T\}$. This is the period in which the Greenfield project is realised and the new power station is put into operation. The modernisation period, represented by τu, describes the period when the retrofitting of the existing capacity takes place and the modernised power plant is put into operation; $\tau_{\mathrm{u}} \in \{0, 1, 2, \ldots, T\}$.

Finally, an amortisation period AP is fixed. This represents the timeframe within which the investment in a new plant or in the modernisation of an existing plant must be amortised.

3.2. Demand

A given, but of course not categorically constant, domestic demand ($\overline{D}_t^{ls}$) is assumed for all production periods, represented by t, and all differentiated electricity load segments, represented by ls; $\mathrm{ls} \in \{1, 2, \ldots, \mathrm{LS}\}$.

3.3. Production

It is assumed that in base period 0, J old plants, represented by j, exist; $j \in \{1, 2, \ldots, J\}$. Some of them are brown coal fired, represented by jb; $j\mathrm{b} \in \{1, 2, \ldots, J\mathrm{B}\}$. Others are old nuclear power stations, represented by jk; $j\mathrm{k} \in \{J\mathrm{B}+1, J\mathrm{B}+2, \ldots, J\mathrm{K}\}$. The remaining old plants are oil, gas, or hard coal fired, represented by js; $j\mathrm{s} \in \{J\mathrm{K}+1, J\mathrm{K}+2, \ldots, J\}$. A maximum of K new power stations, represented by k, can be constructed; $k \in \{1, 2, \ldots, K\}$. Some of them are assumed to be brown coal fired, represented by kb; $k\mathrm{b} \in \{1, 2, \ldots, K\mathrm{B}\}$. The others are gas or hard coal fired, represented by ks; $k\mathrm{s} \in \{K\mathrm{B}+1, K\mathrm{B}+2, \ldots, K\}$. The variable $\mathrm{SO}_{j,\tau_{\mathrm{u}},t}^{\mathrm{ls}}$ describes the power generation of an old plant j, in load segment ls, and production period t using technology of period τ_{u}. If t=2 and τ_{u}=0, the variable describes the production of an old plant in period 2 using technology of base period 0. This means that no modernisation has taken place. If t=2 and τ_{u}=2, the variable stands for the production of an old plant in period 2 using technology of period 2. This means that the plant has been modernised in period 2. The variable $\mathrm{SG}_{k,\tau_{\mathrm{i}},t}^{\mathrm{ls}}$ describes the production of a new plant k, put into operation in period τ_{i}, in load segment ls, and production period t.

The production of old and new plants is bounded by respective capacities ($\mathrm{CAP0}_j$, $\mathrm{CAPG}_{k,\tau_{\mathrm{i}}}$). For the purpose of simplification, it is assumed that there is no capacity expansion if existing plants are modernised. Therefore, the production of modernised old plants can also be bounded by initial capacity ($\mathrm{CAP0}_j$). It will be made clear in the

Variables

TC	Total cost
OC	Operating costs
RFC	Reversible fixed costs
IFC	Irreversible fixed costs
SO	Power generation old plants
SG	Power generation new plants

Binary variables

π	Associated with old capacity
μ	Associated with old but modernised capacity
πg	Associated with new capacity

Indexes

t	Production period	$t \in \{1, 2, ..., T\}$
τi	Greenfield investment period	$\tau i \in \{1, 2, ..., T\}$
τu	Modernisation period	$\tau u \in \{0, 1, 2, ..., T\}$
ls	Load segment	$ls \in \{1, 2, ..., LS\}$
j	Old power plant	$j \in \{1, 2, ..., J\}$
jb	Old brown coal fired power plant	$jb \in \{1, 2, ..., JB\}$
jk	Old nuclear power station	$jk \in \{JB+1, JB+2, ..., JK\}$
js	Old oil, gas or hard coal fired power plant	$js \in \{JK+1, JK+2, ..., J\}$
k	New power plant	$k \in \{1, 2, ..., K\}$
kb	New brown coal fired power plant	$kb \in \{1, 2, ..., KB\}$
ks	New gas or hard coal fired power plant	$ks \in \{KB+1, KB+2, ..., K\}$

Parameters

o	Discount factor
ρ	Discount rate
αo	Operating costs coefficient old plants
αgo	Operating costs coefficient new plants
αr	Reversible fixed costs coefficient old plants
αgr	Reversible fixed costs coefficient new plants
αi	Irreversible fixed costs coefficient old plants
αgi	Irreversible fixed costs coefficient new plants
D	Electricity demand
av	Availability
z	Rate of capacity utilisation
MVB	Energy content maximum brown coal available in a given period
RS	Residual quantity of electricity defined by the law concerning phasing out of nuclear energy

Fig. 1. Symbols used in the model.

following chapter that operating costs are associated with production quantities, while reversible and irreversible fixed costs are associated with capacities.

3.4. Foreign trade

Foreign trade is not considered within the model. Following the study of Hoster (1996), it is assumed that, on balance, future electricity imports and exports will be more or less the same. Thus, it is not necessary to model foreign trade.

4. The model

Formally, the following mixed integer linear program consists of an objective function and several constraints. Total discounted costs are minimised under the following auxiliary conditions: market clearance conditions; capacity constraints regarding old and new power plants; production constraints with respect to brown coal power generation due to the limited availability of brown coal; production constraints regarding nuclear power stations due to the political decision to phase out nuclear energy; and the non-negativity of production quantities. The production quantities of old and new plants ($\mathrm{SO}^{\mathrm{ls}}_{j,\tau_{\mathrm{u}},t}$ and $\mathrm{SG}^{\mathrm{ls}}_{j,\tau_{\mathrm{i}},t}$) are continuous variables. The binary variables ($\pi_{j,t}$, $\mu_{j,t}$, $\pi g_{k,\tau_{\mathrm{i}},t}$) are associated with the capacities of old and new plants. As already mentioned, they ensure that within the model only complete power plants can be constructed, modernised, or shutdown.

Total discounted costs (TC) are a function of the discount factor (o_t), operating costs (OC_t), reversible fixed costs (RFC_t), the cumulative discount factor (o_t^{cum}), and irreversible fixed costs (IFC_t):

$$TC = \sum_t o_t(OC_t + RFC_t) + \sum_t o_t^{\mathrm{cum}} IFC_t. \tag{1}$$

The discount factor (o_t) is a function of the discount rate (ρ):

$$o_t = \frac{1}{(1+\rho)^t} \qquad \text{for all } t. \tag{2}$$

The cumulative discount factor of a given period t (o_t^{cum}) is equal to the sum of (simple) discount factors from this time period t until the time period t+AP, if t+AP≤T:

$$o_t^{\mathrm{cum}} = \sum_{tk=t}^{t+AP} o_{tk} \qquad \text{for all } t + AP \leq T. \tag{3}$$

If t+AP>T, then the cumulative discount factor of a given period t (o_t^{cum}) is equal to the sum of (simple) discount factors from this time period t until the (last considered) time period T. In this case, only the pro-rata investment costs will be considered:

$$o_t^{\mathrm{cum}} = \sum_{tk=t}^{T} o_{tk} \qquad \text{for all } t + AP > T. \tag{4}$$

The operating costs coefficient of a plant is the sum of specific fuel costs, specific operating supplements costs and, if incurred, specific allowance costs (see Fig. 1). The total operating costs of a period t are the sum of all domestic production quantities relevant to this period ($\mathrm{SO}^{\mathrm{ls}}_{j,\tau_{\mathrm{u}},t}$, $\mathrm{SO}^{\mathrm{ls}}_{k,\tau_{\mathrm{i}},t}$), multiplied with the associated cost coefficients ($\alpha o^{\mathrm{ls}}_{j,\tau_{\mathrm{u}},t}$, $\alpha go^{\mathrm{ls}}_{k,\tau_{\mathrm{i}},t}$):

$$\mathrm{OC}_t = \left(\sum_{ls}\sum_{j}\sum_{\tau_{\mathrm{u}}}\alpha o^{\mathrm{ls}}_{j,\tau_{\mathrm{u}},t} SO^{ls}_{j,\tau_{\mathrm{u}},t}\right) + \left(\sum_{ls}\sum_{k}\sum_{\tau_{\mathrm{i}}}\alpha go^{ls}_{k,\tau_{\mathrm{i}},t} SG^{ls}_{k,\tau_{\mathrm{i}},t}\right) \qquad \text{for all } t. \tag{5}$$

The reversible fixed costs coefficient consists of specific personnel costs and specific maintenance costs. The total reversible fixed costs of a period t are the sum of the reversible fixed costs of old and new plants which can be assessed for one plant by multiplying the binary variable ($\pi_{j,t}$, $\pi g_{k,\tau_{\mathrm{i}},t}$) with associated cost coefficient ($\alpha r_{j,t}$, $\alpha gr_{k,\tau_{\mathrm{i}}},t$) and capacity ($\mathrm{CAP0}_j$, $\mathrm{CAPG}_{k,\tau_{\mathrm{i}}}$):

$$RFC_t = \sum_j \pi_{j,t}\alpha r_{j,t}\mathrm{CAP0}_j + \sum_k\sum_{\tau_{\mathrm{i}}} \pi g_{k,\tau_{\mathrm{i}},t}\alpha gr_{k,\tau_{\mathrm{i}},t} CAPG_{k,\tau_{\mathrm{i}}} \qquad \text{for all } t. \tag{6}$$

This formulation assures that, if a power station is in use and the associated binary variable is therefore equal to 1, the reversible fixed costs are incurred in full, independent of production.

The irreversible fixed costs are the capital costs incurred through the modernisation of old plants or through the construction of new plants. Multiplying the binary variable ($\mu_{j,t}$, $\pi g_{k,\tau_{\mathrm{i}},t}$) with associated cost coefficient ($\alpha i_{j,t}$, $\alpha gi_{k,\tau_{\mathrm{i}},t}$) and capacity ($\mathrm{CAP0}_j$, $\mathrm{CAPG}_{k,\tau_{\mathrm{i}}}$) produces an assessment of these costs:

$$IFC_t = \sum_j \mu_{j,t}\alpha i_{j,t}\mathrm{CAP0}_j + \sum_k\sum_{\tau_{\mathrm{i}}} \pi g_{k,\tau_{\mathrm{i}},t}\alpha gi_{k,\tau_{\mathrm{i}},t} CAPG_{k,\tau_{\mathrm{i}}} \qquad \text{for all } \tau_{\mathrm{i}} = t. \tag{7}$$

The multiplication of capital costs for a period t with the cumulative discount factor (see Eq. (1)) assures that the (total or pro-rata) investment is completely written off during the remaining lifetime.

The first auxiliary conditions assure market clearance:

$$\sum_j\sum_{\tau_{\mathrm{u}}} SO^{ls}_{j,\tau_{\mathrm{u}},t} + \sum_k\sum_{\tau_{\mathrm{i}}} SG^{ls}_{k,\tau_{\mathrm{i}},t} \geq \overline{D}^{ls}_t \qquad \text{for all } ls, t. \tag{8}$$

The production of an old plant over all load segments is restricted to its capacity multiplied by its availability (av_j) and by the time units per chosen time period (pt). This is 8760 hours for 1 year. The parameter (z_{ls}) describes the rate of capacity utilisation, associated with production within a certain load segment. For base load power generation, the rate of capacity utilisation is equal to 1. Production can exhaust the quantity of electricity as defined by availability, capacity, and time units for the entire time period selected. For middle load power generation and a rate of capacity utilisation of, for example 0.5, a maximum of half this electricity quantity can be produced:

$$\sum_{ls}\sum_{\tau_u}\frac{1}{z^{ls}}SO^{ls}_{j,\tau_u,t}\leq\pi_{j,t}\left(av_j\ pt\ \mathrm{CAP0}_j\right)\qquad \text{for all } j,t. \tag{9}$$

The following inequality assures that the production of an old plant with modernised technology can only take place if the associated capacity was also modernised (that means that the respective binary variable $\mu_{j,t}$ is equal to 1):

$$\sum_{ls}\frac{1}{z^{ls}}SO^{ls}_{j,\tau_u,t}\leq\mu_{j,t}\left(av_j\ pt\ \mathrm{CAP0}_j\right)\qquad \text{for all } j,\tau_u=t. \tag{10}$$

The production in period $t+s$, $s\in\{1, 2,\ldots, T-s\}$, with modernised technology implemented in period t, can only take place if the plant was in fact modernised in period t (that means that the binary variable $\mu_{j,t}$ has to be equal to 1):

$$\sum_{ls}\frac{1}{z^{ls}}SO^{ls}_{j,\tau_u,t+s}\leq\mu_{j,t}\left(av_j\ pt\ \mathrm{CAP0}_j\right)\qquad \text{for all } j,\tau_u=t,s. \tag{11}$$

K new plants (each with a given capacity of CAPG_{k,τ_i}) can be constructed in each period. The production is similar to old plants bounded by capacity:

$$\sum_{ls}\frac{1}{z^{ls}}SG^{ls}_{k,\tau_i,t}\leq\pi g_{k,\tau_i,t}\left(av_{k,\tau_i}\ pt\ CAPG_{k,\tau_i}\right)\qquad \text{for all } k,\tau_i,t. \tag{12}$$

Production in period $t+s$ can only take place if the plant was in fact constructed in period t (that means that the binary variable $\pi g_{k,\tau_i},t$ is equal to 1):

$$\sum_{ls}\frac{1}{z^{ls}}SG^{ls}_{k,\tau_i,t+s}\leq\pi g_{k,\tau_i,t}\left(av_{k,\tau_i}\ pt\ CAPG_{k,\tau_i}\right)\qquad \text{for all } k,\tau_i=t,s. \tag{13}$$

The production of the brown coal fired plants is bounded by the energy content of the maximum amount of brown coal available per period (MVB_t). The net efficiency (ef_{j_b},τ_u and ef_{k_b},τ_i) associates output (power generation) and input (energy content):

$$\sum_{ls}\sum_{j_b}\sum_{\tau_u}\frac{1}{ef_{j_b,\tau_u}}SO^{ls}_{j_b,\tau_u,t} + \sum_{ls}\sum_{k_b}\sum_{\tau_i}\frac{1}{ef_{k_b,\tau_i}}SG^{ls}_{k_b,\tau_i,t}\leq MVB_t\qquad \text{for all } t. \tag{14}$$

Later, three scenarios will be presented. Two of them assume the phasing out of nuclear energy according to the law passed in 2001. For these two scenarios, the production of nuclear power stations is bounded by the residual electricity quantity (RS) defined by this law:

$$\sum_{t}\sum_{ls}\sum_{jk}\sum_{\tau_u}SO^{ls}_{jk,\tau_u,t}\leq RS. \tag{15}$$

Some combinations of investment, modernisation and production period are not valid. It has to be assured that production with these invalid combinations is equal zero. With respect to old plants, the modernisation period has to be equal to or less than the production period. Production in period t cannot be realised with a technology not available in period t:

$$SO^{ls}_{j,\tau_u,t} = 0 \qquad \text{for all } j,\ ls,\ \tau_u > t. \tag{16}$$

Analogous, production of a new plant in period t can only take place if the plant was already constructed in period t:

$$SG^{ls}_{k,\tau_i,t} = 0 \qquad \text{for all } k,\ ls,\ \tau_i > t. \tag{17}$$

$\pi_{j,t}, \mu_{j,t}, \pi g_{k,\tau_i,t}$ are binary variables. The non-negativity condition must hold for all other (continuous) variables. Production quantities have to be greater than or equal to zero:

$$SO^{ls}_{j,\tau_u,t}, SG^{ls}_{k,\tau_i,t} \geq 0 \qquad \text{for all } ls,\ j,\ k,\ \tau_i,\ \tau_u,\ t. \tag{18}$$

5. Scenario design and model parameters

In the following, four scenarios are developed. They differ in terms of the expectations of the future political constellation. The base scenario (BASE) assumes that the phasing out of nuclear energy will be realised, as well as implementing the CO_2 allowance model as defined by an EU directive. It is presumed that allowance prices will be high enough to evolve the desired allocation effects. The scenario without allowances (WOAL) assumes that the CO_2 allowance model will not be realised or will not be effective, while the scenario with allowances but without phasing out of nuclear energy (WOPONE) presumes that the allowance model will be effective and that the phasing out of nuclear energy will not be realised. The scenario without policy measures (WOPM) assumes that both the allowance model as well as phasing out of nuclear energy will not be realised. Moreover, in this case, the construction of new nuclear power stations is not expected and not valid.

The scenarios differ only with respect to the question of whether CO_2 allowances are introduced or not, and with respect to whether or not nuclear energy is phased out. Model parameters are otherwise the same for all scenarios.

The model assumptions and model formulation discussed in Sections 3 and 4 have already shown that time horizon and discount rate, electricity demand, cost coefficients, capacity of plants, and other restrictions (such as brown coal availability) are important model parameters. They are presented in this order.

5.1. Time horizon and discount rate

The calculations are made for 5-year periods up until 2026/30. As usual in literature (see, e.g., Hoster, 1996; Nollen, 2003) the discount rate is 8%.

5.2. Electricity demand

Only conventional power plants are considered. The expansion of non-conventional power plants is (predominantly) not market-driven but rather the result of government aid which should not be discussed and analysed here in detail. Moreover, the modelling is based on the idealised so-called IKARUS power plant inventory (see FIZ, 2001) which covers power stations used for public electricity supply. Small power plants are not considered in the model calculations. To identify the relevant demand, it is therefore necessary to adjust the total (expected) net electricity generation for electricity production in non-conventional, non-public, small power stations. The majority of studies (see, for example, Prognos, EWI and BEI, 2001; Nollen, 2003) presume that total net power generation will increase slightly up until 2020. For the years following that, an unchanged total net power generation is assumed. Because of the increasing importance of power generation in non-conventional power stations, it is assumed that the relevant demand will decrease from 400 at present to 330 TWh per year in the period 2026/30 (Table 1).

Six load segments are differentiated within the model (see also Table 5). If the minimum and maximum loads are known, the distribution of demand on load segments can be determined using an idealised annual load duration curve (for detail see, e.g., Nollen, 2003). It is presumed that the percentage proportioning of demand on load segments does not change over time.

5.3. Cost coefficients and capacities

The model distinguishes between old (or existing) and new power plants. Tables 2 and 3 present the relevant parameters for old and new plants. The construction of new nuclear power stations is not valid. Fig. 2 shows how to estimate cost coefficients from the parameters presented in Tables 2 and 3. Additionally, fuel prices as compiled in Table 4, are necessary for the calculation of fuel costs. The price of brown coal is estimated by

Table 1
Assumed relevant electricity demand (in TWh)[a]

	2001/05	2006/10	2011/15	2016/20	2021/25	2026/30
Gross electricity production	580	587	593	600	600	600
−Self consumption	46	47	47	48	48	48
=Net electricity production	534	540	546	552	552	552
Thereof, public power plants	459	464	469	475	475	475
−Wind	17	38	59	80	88	96
−Hydropower	25	26	27	28	28	28
−Miscellaneous regenerative energy sources	8	10	12	14	16	18
=Net electricity production of public conventional power plants	417	400	383	367	359	351
−Small power stations	18	18	17	16	16	15
=Net electricity relevant production/demand	399	383	367	351	343	335

[a] Own calculations based on Prognos, EWI and BEI (2001) and Nollen (2003).

Table 2
Old power plants 2001/05[a]

Type		OP-HC Type 700	OP-HC Type 600a	OP-HC Type 600b	OP-HC Type 300	OP-BC Type 800	OP-BC Type 600	OP-BC Type 300	OP-NP Type 1300	OP-NP Type 1100	OP-GAS Type 600	OP-GCC Type 300	OP-OIL Type 500
Year of construction	(YC)	1991/05	1981/90	1971/80	1961/70	1991/05	1971/80	1961/70	1981/90	1971/80	1971/80	1991/05	1971/80
Net capacity	(MW_{el})	700	600	600	300	800	600	300	1285	1100	600	300	500
Efficiency	(%)	42	38	37	34	41	35	33	34	33	39	55	25
Availability	(%)	83	80	80	80	84	80	79	83	83	85	85	83
Number of units		3	15	7	26	13	11	13	10	8	19	11	12
Supplementary specific operating costs	(€ /kWh)	0.00175	0.00175	0.00175	0.00175	0.00275	0.00275	0.00275	0.0006	0.0006	0.0005	0.0005	0.0005
Specific manpower Requirements	(Workers/ a/MW)	0.135	0.135	0.135	0.135	0.15	0.15	0.15	0.11	0.11	0.03	0.03	0.03
Wage rate	(€ /a/Worker)	45 000	45 000	45 000	45 000	45 000	45 000	45 000	45 000	45 000	45 000	45 000	45 000
Specific maintenance costs	(€ /kW/a)	21	21	21	21	25	25	25	30	30	9	9	9
Specific investment costs modernisation	(€ /kW)	30	33	33	39	30	33	39	26	30	n.p.	n.p.	n.p.

OP=Old plant; HC=Hard coal; BC=Brown coal; NP=Nuclear power; GCC=Gas combined cycle; n.p.= not permitted.

[a] Nollen (2003) [updated].

Table 3
New power plants[a]

Type		NP-HC-Type 800	NP-HC Type 900a	NP-HC Type 900b	NP-BC Type 950	NP-BC Type 1000	NP-GCC Type 800	NP-GCC Type 900
Year of construction	(YC)	2006/15	2016/25	2026/30	2006/15	2016/30	2006/15	2016/30
Net capacity	(MW_{el})	800	900	900	950	1000	800	900
Efficiency	(%)	49	50	51	45	49	58	62
Availability	(%)	87	89	89	84	84	85	85
Supplementary specific operating costs	(€ /kWh)	0.00175	0.00175	0.00175	0.00275	0.00275	0.0005	0.0005
Specific manpower requirements	(Workers/a/MW)	0.135	0.135	0.135	0.15	0.15	0.03	0.03
Wage rate	(€ /a/worker)	45 000	45 000	45 000	45 000	45 000	45 000	45 000
Specific maintenance costs	(€ /kW/a)	21	21	21	25	25	9	9
Specific investment costs	(€ /kW)	1050	1000	950	1200	1200	500	500

NP=New plant; HC=Hard coal; BC=Brown coal; GCC=Gas combined cycle.

[a] Nollen (2003).

totalling the specific operating cost and reversible fixed costs of coal mining. Brown coal is not tradable because of high transport costs. Therefore, brown coal usage is only ensured as long as these cost components are covered. Moreover, surcharges on operating costs for hard and brown coal fired plants are assumed if these are used for middle or peak load electricity production (Table 5) due to decreasing efficiencies. It is presumed that nuclear power stations are only used for base load power generation.

The base scenario (BASE) as well as the scenario without the phasing out of nuclear energy (WOPONE) assume that the CO_2 allowance model will be effective. The emerging allowance costs are a component of operating costs. Future allowance costs are determined by CO_2 emission factors for fuels (Table 6); net efficiencies of old and new plants (Tables 2 and 3); and assumed allowance prices (Table 7). The future allowance prices presented in Table 7 are conservative estimations in comparison with those of the European Commission (2001) which expects a price of 20 to 33 euro per ton of CO_2 in the medium term.

Operating costs of base load power generation in the base period 2001/05 are approximately1.3 euro cents per kWh for most modern operating hard coal fired power plants; approximately 1.2 to 1.3 euro cents for most modern operating brown coal fired power stations; approximately 0.4 euro cents for nuclear power stations; and about 2.1 euro cents for most modern, gas combined-cycle power stations. The expected allowance prices would reduce the competitiveness of coal, in particular brown coal-based power generation. No additional costs arise for nuclear power stations. Assuming an allowance price of 5 euro per ton of CO_2, additional costs for most modern gas combined-cycle power plants are 0.18 euro cents per kWh, 0.41 for hard coal fired power plants, and 0.44 euro cents for brown coal fired power plants. The surcharge for coal-based power generation is in this case more than 30%! If allowance prices are 15 to 20 euro per ton of CO_2, then this means that the allowance costs are higher than the other operating costs (fuel costs and operating supplement costs).

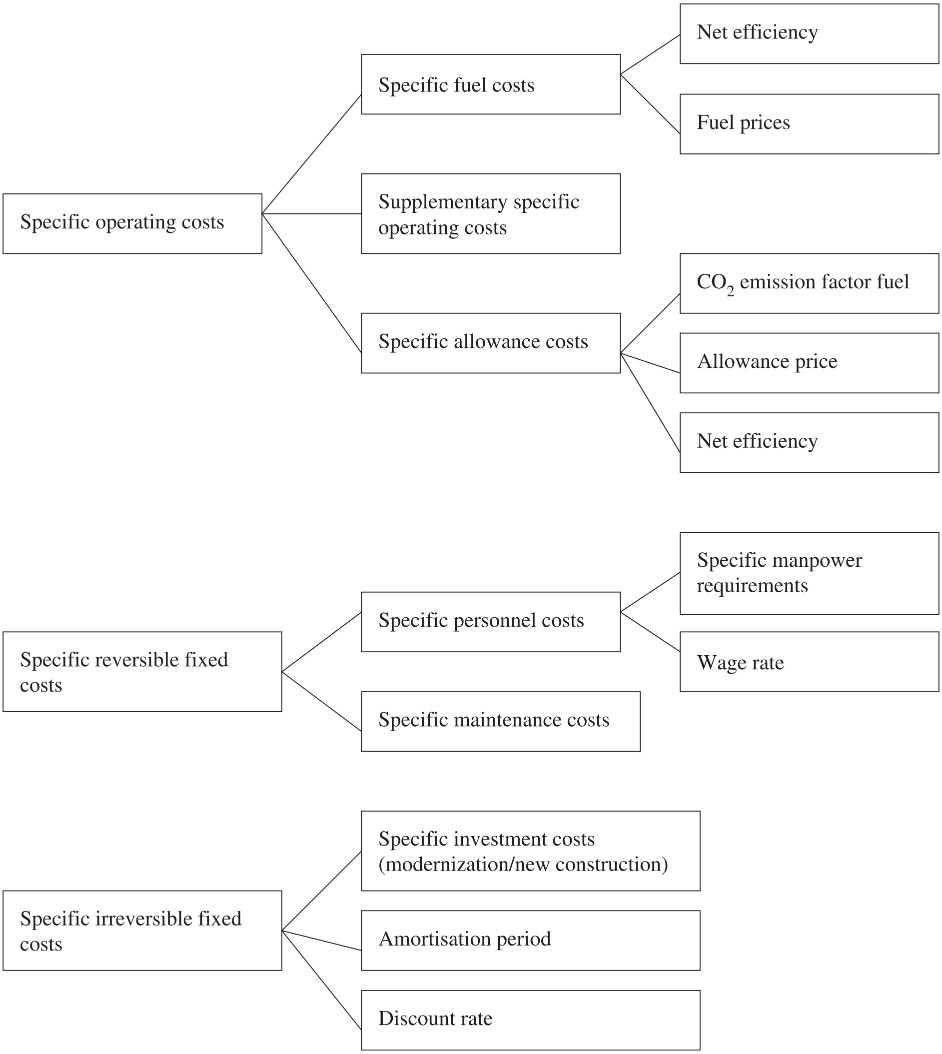


Fig. 2. Determination of cost coefficients.

It is presumed that maintenance costs will rise by 3% a year for coal fired and nuclear power plants and 8% a year for gas- and oil-based power plants if power stations are more than 30 years old. Abrasion and the resulting maintenance costs are assumed to be higher for gas- and oil-based power plants because existing gas- and oil-based power plants are mostly used for peak and middle load power generation. The number of cold starts and therefore the extent of abrasion is remarkably higher than for existing coal fired and nuclear power plants which are mostly used for base load power generation (see Markewitz and Vögele, 2003 and Table 8).

It is assumed that all older brown coal fired power plants and all existing nuclear power stations have been modernised in the last few years (see Author not stated, 2003) and that

Table 4
Fuel prices

		2001/05	Changes per year (%)
Hard coal	€ /GJ	1.3	1
Natural gas	€ /GJ	3.1	1.5
Brown coal	€ /GJ	1.0[a]	1
Nuclear fuel	€ /MWh	1.2	1

[a] Not full costs (only variable costs and reversible fixed costs).

the modernisation is reflected within the presented data. In contrast, it is assumed that hard coal fired power stations have not been modernised in the last few years. It is presumed within the model that modernisation every 5 years can improve net efficiency by 0.75% points. Thus, a first-time modernisation after 20 years will lead to an increase in net efficiency of 3% points. Publications of power plant operators (see, e.g., Kraftwerk Mehrum, 2003) and technology suppliers (see, e.g., Siemens, 2003) were used for the assessment of investment costs for modernisation. The central measure was usually the replacement and optimisation of the steam turbine.

It is assumed that a maximum of 12 new power plants of each type are put into operation per 5-year period; that is 12 brown coal, 12 hard coal fired, and 12 gas combined-cycle power plants. A total of 12 power stations of each type together represent about 31 GW_{el} and therefore more than 35% of current net capacity.

5.4. Other restrictions

It is assumed that a maximum of 175 million tons of brown coal are mined each year. The lower heating value is 9 GJ per ton. Therefore, the energy content of available brown coal is 440 TWh. Two of the scenarios assume a phasing out of nuclear energy. The residual quantity of electricity for nuclear power stations is about 1.700 TWh for the years after 2005 in accordance with the 2001 law.

6. Model results

The results of the model are presented in this chapter. Firstly, the results are discussed for the total future reconstruction of old capacity. Then, the results are presented relating to

Table 5
Surcharge (for load segments other than base load) in percent (%) of operating costs exclusive of allowance costs

	Capacity utilization (%)	Oil/natural gas	Hard coal	Brown coal	Nuclear power
Base load	100	0	0	0	0
Middle load 1	90	0	2	3	
Middle load 2	70	0	4	6	Not permitted.
Middle load 3	50	0	6	9	Only base load allowed.
Middle load 4	30	0	8	12	
Peak load	10	0	10	15	

Table 6
CO_2 emission factors (referring to the lower heating value) (t CO_2/GJ)[a]

Brown coal	0.100
Hard coal	0.095
Natural gas	0.055
Oil (heavy)	0.078

[a] BMU (2003).

the future requirement for total new conventional power generation capacity; to the share of new and total capacity provided by various energy sources; and relating to the modernisation activities of existing plants. Finally, model parameters which are critical for the results of the model are discussed.

6.1. Total reconstruction of old capacity

Fig. 3 shows the total reconstruction of old capacity according to the optimisation calculations and according to an assumed fixed power plant lifetime of 30 and 35 years, denoted as LT30 and LT35 respectively. By 2020, the policy scenarios with allowances (BASE, WOPONE) predict a reconstruction of old capacity close to the figures estimated in the scenario of a fixed lifetime of 35 years (LT35), while the reconstruction of old capacity estimated by the scenarios without allowances (WOAL, WOPM) is lower. After 2020, only the base scenario (BASE) predicts a reconstruction of old capacity that is close to the figures produced in the scenario of a fixed lifetime of 35 years (LT35).

The pace of reconstruction of old capacity is highest for the base scenario (BASE) followed by the scenario without the phasing out of nuclear energy (WOPONE). The pace tends even to be underestimated in the base scenario (BASE) because the limit of a maximum of 12 new gas combined-cycle power plants (equal to 9.6 GW_{el} net capacity) is reached for the first four 5-year periods. It is lowest for the scenario without policy measures (WOPM). This is not surprising. Without an effective allowance model and without the phasing out of nuclear energy, the necessity for a comprehensive reorientation of the power plant inventory is least.

These first scenario results already clarify that the pace of old capacity reconstruction greatly depends on the assumptions about the future political constellation. The base scenario (BASE), for example, predicts that the old net power generating capacity still in operation in 2026/30 will be about 20 $GW_{el,}$ while the scenario without policy measures predicts a figure of more than 50 GW_{el}.

Table 8 shows the average age of retired old plants according to the policy scenarios and the critical technical age of existing power plants as estimated by Markewitz and Vögele (2003).

Table 7
Assumed allowance price (€/t CO_2)

Period	2001/05	2006/10	2011/15	2016/20	2021/25	2026/30
Price	0	5	10	15	20	25

Table 8
Average age of retired old plants [and-in brackets-average age of old power plants in operation in 2026/30] (in years; based on capacity)[a]

	Results of the optimization model				For maximum 250,000
	BASE	WOAL	WOPONE	WOPM	full-load hours
Hard coal	40 [39]	47 [46]	36 [30]	46 [42]	37
Brown coal	35 [32]	40 [42]	32 [31]	43 [34]	37
Natural gas	37 [31]	32 [31]	34 [31]	35 [31]	34
Oil	28 [. . .]	28 [. . .]	28 [. . .]	28 [. . .]	24
Nuclear power	33 [. . .]	33 [. . .]	. . . [46]	. . . [46]	34
Total	35 [34]	33 [43]	33 [41]	38 [41]	n.a.

n.a.=not available.
[a] Model calculations; Markewitz and Vögele (2003).

Markewitz and Vögele (2003) assume that 250,000 full-load hours are a critical value for power plants. Plants will have reached a critical technical condition then and will have to be checked more often. They presume a penalty of 40 hours for cold starts.

The average age of retired old plants also greatly depends on the assumptions about the future political constellation. The average age of retired old hard coal-based power plants is, for example, 36 years for the scenario without the phasing out of nuclear energy (WOPONE) and 47 years for the scenario without allowances (WOAL). The average age of retired old brown coal-based power plants is 32 years for the scenario without the

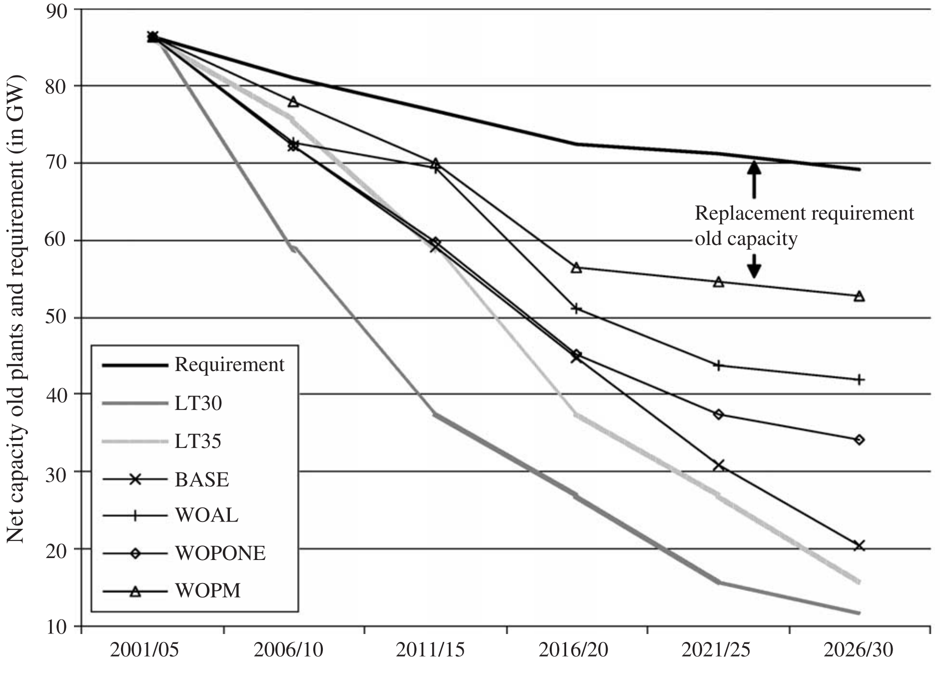


Fig. 3. Reconstruction of old capacity and replacement requirement (in GW_{el} net capacity). (Model calculations).

phasing out of nuclear energy (WOPONE) and 43 years for the scenario without policy measures (WOPM). The critical technical age is, as a rule, within this range. The economically motivated age retirement of old plants is remarkably higher than the critical technical age only in the case of hard coal-based power plants if no allowances are assumed (WOAL, WOPM) and in the case of nuclear power stations if no phasing out of nuclear energy is assumed (WOPONE, WOPM).

Existing power stations are retired, on average, after 33 to 38 years according to the optimisation calculations (Table 8). The values for the scenarios without allowance (WOAL) and without the phasing out of nuclear energy (WOPONE), as well as for the scenario without policy measures (WOPM) have only limited application (as do some of figures that refer to single power plant types). In all these cases, at the end of the considered time framework, a significant amount of old capacity is still in use which is significantly older (Table 8, figures in brackets) than the average age of the old plants retired by the end of the considered time framework. The old but still functioning (coal-based or nuclear) power stations have no effect on the average age of retired plants.

6.2. Total new capacity construction

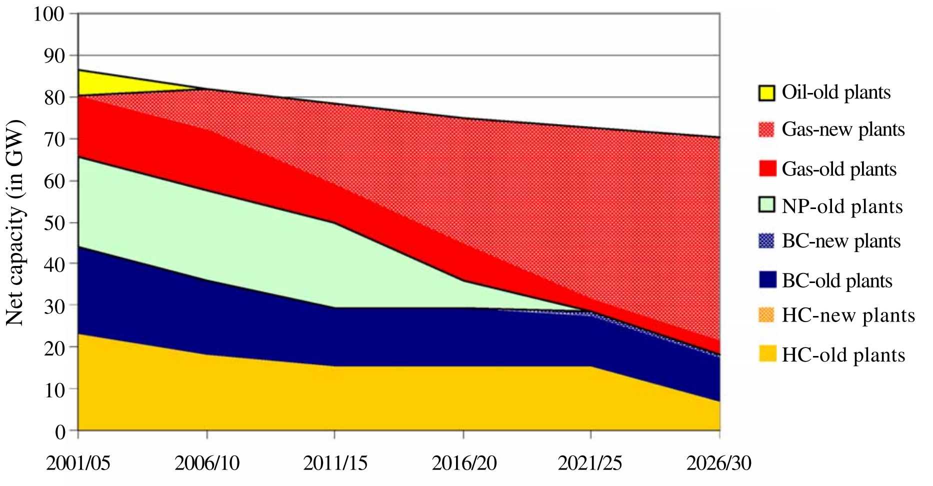
Table 9 shows the total new construction of conventional power-generating capacity. According to the optimisation calculations, 19 to 31 GW_{el} of new net capacities will have been constructed by the year 2020. New plants account for about 25 to 42% of the total capacity necessary in 2020. This is a remarkably lower share than the existing studies (Enquete Commission, 2002; UBA, 2003; Markewitz and Vögele, 2003) presented in Section 1 have estimated (60% to 70%). As already emphasized, however, these existing studies also consider nonconventional power plants. Power generation and capacity of nonconventional power plant will presumably expand greatly (see Table 1). The percentage figures mentioned above therefore overestimate the differences between the existing studies and the results of scenario calculations. The values for the scenarios with allowances (BASE, WOPONE) should indeed be close to the values in the existing studies, although the figures for new construction are lower for the policy scenarios without allowances (WOAL, WOPM).

Table 9
Requirement for new net power generation capacity (in GW_{el})[a]

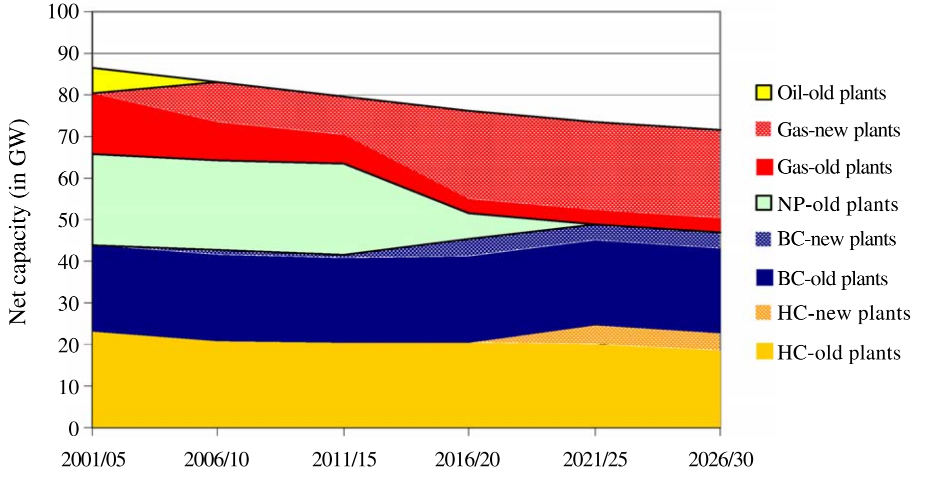
	BASE	WOAL	WOPONE	WOPM
2006/10	10	11	10	4
2011/15	10	1	9	6
2016/20	11	14	11	9
2021/25	12	5	5	0
2026/30	9	0	2	0
2006/20	30	25	29	19
2006/30	51	30	37	19

[a] Model calculations.

a) BASE



b) WOAL



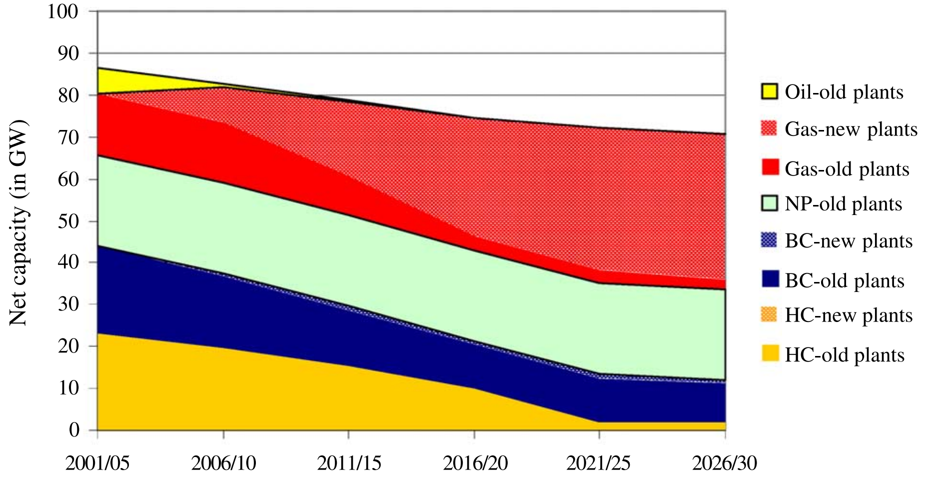
NP = Nuclear power; BC = Brown coal; HC = Hard coal.

Fig. 4. (a–d) Share of new and total capacity from various energy sources (in GW_{el} net capacity). (Model calculations).

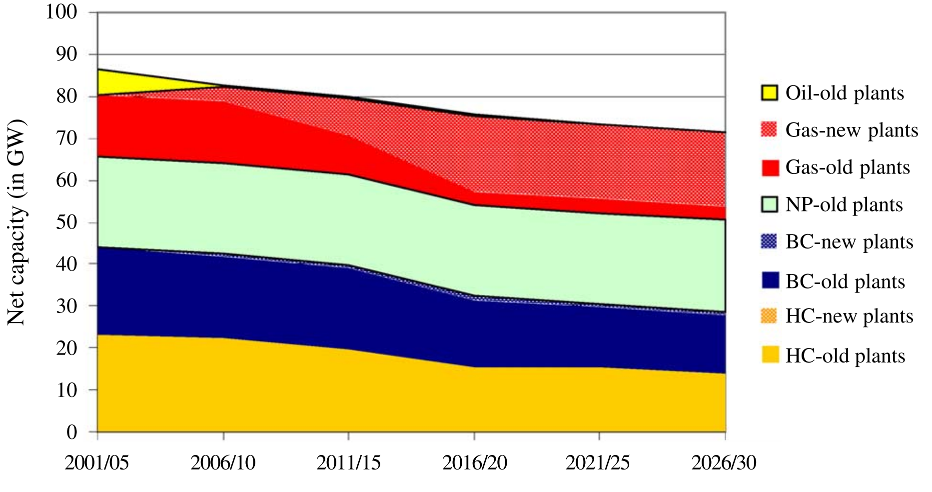
6.3. Share of new and total capacity provided by various energy sources

Fig. 4 shows the share of new and total capacity provided by various energy sources. The gas-based net power generation capacity expands from 15 currently to about 52 GW_{el} for the year 2030 according to the base scenario (BASE). The trend towards gas is very

c) WOPONE



d) WOPM



NP = Nuclear power; BC = Brown coal; HC = Hard coal.

Fig. 4 (continued).

strong in the first four periods. The maximum of 12 new power plants per 5-year period is exhausted. Nuclear energy is phased out by 2020 for political reasons. The hard coal-based net power generation capacity decreases from 23 currently to about 7 GW_{el}, and the brown coal-based capacity declines from almost 21 at present to about 11 GW_{el} due to economic discrimination resulting from the CO_2 allowance model.

As in the base scenario, natural gas gains shares in the scenario without allowances (WOAL). However, the net capacity of 25 GW_{el} reached in 2030 is much lower. As in the base scenario, the retirement of nuclear power stations is politically motivated. The brown coal-based capacity increases particularly after the retirement of nuclear power stations. Hard coal power stations lose only very small proportions of capacity.

Again, natural gas gains shares in the scenario with allowances but without the phasing out of nuclear energy (WOPONE). The capacity expands to about 37 GW_{el} in 2030. The existing nuclear power stations remain in operation and are the second winners in this political scenario. According to this scenario, coal-based power generation loses significant shares of capacity.

The scenario without policy measures (WOPM) predicts a moderate expansion of gas-based power generation capacity similar to the scenario without allowances. The existing nuclear power stations remain in operation, while the share of coal-based power generation capacity declines slightly.

If the allowance model is introduced and is effective, gas is the biggest winner in the energy source competition. Furthermore, this dominance will be greater with the phasing out of nuclear energy than without. In the scenarios without the CO_2 allowance model, the expansion of gas-based power generation will be comparatively moderate. With the phasing out of nuclear energy, brown coal-based power generating capacity will increase and hard coal-based power generation will remain more or less constant. Without the phasing out of nuclear energy, brown and hard coal-based power generation capacity will decline slightly.

6.4. Modernisation activities

The modernisation of old capacity is shown in Table 10. According to scenario calculations, 18 to 32 GW_{el} cumulative old net power generation capacity is modernised by 2020. Modernisation activities are greatest for the scenarios with allowances (BASE, WOPONE) because increasing allowance prices and thereby increasing opportunity costs make the modernisation of existing plants more attractive. All of the 700 MW_{el} and some of

Table 10
Modernisation activities[a]

	BASE		WOAL		WOPONE		WOPM	
	In GW_{el}	As share of existing old capacity (%)	In GW_{el}	As share of existing old capacity (%)	In GW_{el}	As share of existing old capacity (%)	In GW_{el}	As share of existing old capacity (%)
2006/10	15	20	10	14	15	21	13	16
2011/15	7	12	9	13	10	17	3	4
2016/20	10	23	7	14	2	5	2	4
2021/25	8	25	4	8	10	28	12	21
2026/30	9	42	7	16	32	93	31	59
2006/20	32		27		28		18	
2006/30	48		37		70		61	

[a] Model calculations.

the 600 MW_{el} hard coal-based generating units are modernised twice and all of the 800 MW_{el} brown coal-based generating units are modernised once by 2020. In contrast, all of the 700 MW_{el} hard coal, a greater or lesser share of the 600 MW_{el} hard coal and only a small share of the 800 MW_{el} brown coal-based generating units are modernised once in the scenarios without allowances (WOAL, WOPM) by the year 2020. In the years after 2020, modernisation activity is greatest for the scenarios without the phasing out of nuclear energy (WOPONE, WOPM). The reason in both cases is, predominantly, the modernisation of all nuclear power stations, which represent 21 GW_{el} of net capacity, in the period 2026/30.

6.5. Critical model parameters

The developed modernisation model minimises discounted costs of power production under defined auxiliary conditions, such as the market clearance condition. Accordingly, apart from demand parameters, all model parameters which dominate comparative costs of production alternatives, i.e., power stations of different types, have a wide-ranging influence on the results of the model. These are primarily:

6.5.1. Discount rate

A higher or lower discount rate would, respectively, either decelerate or accelerate old capacity reconstruction. Moreover, the rate will lead to either advantages or disadvantages for those technologies with comparably low investment costs, like new gas combined-cycle power stations as compared with new coal-based power plants.

6.5.2. Fuel prices

The assumptions on future fuel prices are highly critical because they have significant influence on model results and are very difficult to predict. A sharper or less sharp increase in the fuel price of one energy source would, ceteris paribus, result in either disadvantages or advantages for those power plant types that use this energy source. The price increase for gas is assumed, for example, to be 1.5% per year for all scenario calculations, while the price increase for the other energy sources is assumed to be lower at 1% per year (see Table 4). If the (comparative) increase in gas price is even greater, then the scenario calculations overestimate the expansion of gas-based power generation. A comparison of the base scenario (BASE) with the scenario without allowances (WOAL) illustrates the extent of the influence of fuel prices and associated costs on model results. The allowance costs assumed in the base scenario discriminate as a surcharge on prices of fossil fuels coal-based power generation.

6.5.3. Efficiencies

Assumptions on the technical parameters of power plants, in particular on efficiencies of new power plants and efficiency gains through modernisation, play an important role. Higher (lower) efficiencies of new power plants accelerate (decelerate), ceteris paribus, the reconstruction of old capacity. In contrast, higher (lower) efficiency gains of old plants through modernisation decelerate (accelerate), ceteris paribus, the reconstruction of old capacity. The influence of assumptions about efficiency gains through modernisation on model results will be discussed in detail in Section 7.

6.5.4. Maintenance costs

Many existing power plant models, such as that presented by Peek et al. (2004), assume a fixed power plant lifetime or, in other words, infinitely high maintenance costs after 30 to 40 years of service. The developed model assumes increasing maintenance costs of 3% to 8% per year after 30 years. If a higher (lower) rate of increase in maintenance costs is assumed, then old plant reconstruction is accelerated (decelerated).

Despite the significant influence of some critical parameters on model results, some important consequences of scenario calculations remain. Obviously, the pace of old capacity reconstruction greatly depends on the future political constellation. The pace is fastest in the case of an effective allowance model and the phasing out of nuclear energy; it is slowest in the case without policy measures. From this point of view, the assumption of a fixed lifetime of power plants made by several previous studies seems highly problematic. The same is true for the disregard of a modernisation option for old plants in power plant models as shown in the following section.

7. Discrepancies between models with and without modernisation option

The assumptions about efficiency gains through modernisation of old plants have a significant influence on model results as previously discussed. The extent of this influence can be seen in Table 11 with respect to the reconstruction of old capacity. So far, it has

Table 11
Old capacity in the case with and without modernization option for old plants, respectively (in GW_{el} net capacity)[a]

	BASE	Variations of BASE		WOAL	Variations of WOAL	
		No modernisation	Greater efficiency gains[b]		No modernisation	Greater efficiency gains[b]
2001/05	86	86	86	86	86	86
2006/10	72	72	71	73	71	74
2011/15	59	58	58	69	63	67
2016/20	45	39	44	51	47	52
2021/25	31	26	31	44	38	46
2026/30	21	18	28	42	36	43
	WOPONE	**Variations of WOPONE**		**WOPM**	**Variations of WOPM**	
		No modernisation	Greater efficiency gains[b]		No modernisation	Greater efficiency gains[b]
2001/05	86	86	86	86	86	86
2006/10	72	72	73	78	78	78
2011/15	60	59	61	70	70	69
2016/20	45	44	47	56	56	62
2021/25	37	37	45	55	55	56
2026/30	34	25	42	53	53	55

[a] Model calculations.

[b] Modernisation can improve every five years the net efficiency by 1.5% (instead of 0.75%) points.

been assumed that modernisation every 5 years can improve net efficiency by 0.75% points. Now the discrepancies in model results are studied if a zero and a double efficiency gain (1.5% points every 5 years) is presumed for all four policy scenarios.

Without the modernisation option, the reconstruction of old capacity is most extensive. It is, as a rule, least extensive if the double efficiency gain is assumed. The discrepancies with respect to reconstruction of old capacity are in part remarkable. Depending on the assumptions about efficiency gains through modernisation, old capacity exists in a range from 18 to 28 GW_{el} in the period 2026/30 for the base scenario (BASE); 36 to 43 GW_{el} for the scenario without allowances (WOAL); 25 to 42 GW_{el} for the scenario without the phasing out of nuclear energy (WOPONE); and 53 to 55 GW_{el} for the scenario without policy measures (WOPM).

These results show that modernisation activities should be integrated in power plant models because the discrepancy between models that include a modernisation option and those that do not include it can be considerable. Besides, it becomes clear that the extent of assumed possible efficiency gain has a great effect on model results. Therefore, additional work is necessary to verify the simplifying assumption of an efficiency gain of 0.75% points every 5 years for all power plant types. Further research is required to determine whether or not a differentiation for the different types of existing power plants is necessary. Additionally, it remains to be investigated whether or not a differentiation of modernisation strategies for one type of power plant would provide further advance.

8. Summary and perspective

The objective of this paper was to assess the economically motivated construction of new conventional power plants, and the modernisation of existing conventional power plants in Germany using an optimisation model. The scenario calculations show that the pace of old capacity reconstruction greatly depends on assumptions about the future political framework. The same is true for the average age of retired old plants. From this point of view, the fixed lifetime for an old plant assumed in many studies and for power plant models is highly problematic. According to scenario calculations, the pace of reconstruction of old capacity by 2020 is in the case of an effective CO_2 allowance model close to the values in the existing studies presented in Section 1. The pace is considerably slower in the cases without an effective CO_2 allowance model, in particular if this coincides with an assumed lack of phasing out of nuclear energy. By 2020, modernisation activities are most extensive in the cases of an effective CO_2 allowance model. All of the 700 MW_{el} and some of the 600 MW_{el} hard coal-based generating units are modernised twice and all of the 800 MW_{el} brown coal-based generating units once by 2020. After 2020, modernisation activities are most extensive in the cases without the phasing out of nuclear energy. The main reason is that all of the nuclear power stations are modernised in this period. An effective CO_2 allowance model leads to the dominance of gas-based power generation. This dominance is greatest if a simultaneous phasing out of nuclear energy is assumed. In the cases without an effective CO_2 allowance model, coal-based power generation will remain a central element of power generation along with gas and, if nuclear energy is not phased out, with nuclear energy.

The optimisation model applied considers the modernisation of old plants as an investment alternative to the construction of new plants. This is an improvement on existing power station models. Estimates show that discrepancies between models that include plant modernisation and models that do not include it can be considerable, depending on scenario assumptions. It is assumed in a simplified manner that modernisation leads to the same lifetime-dependent efficiency gains for all existing nuclear and coal-fired power stations. Further studies are required to determine whether or not a differentiation for the different types of existing power plants is necessary. Additionally, it remains to be investigated whether or not a differentiation of modernisation strategies for one type of power plant would represent an advance. Different modernisation strategies would then lead to different efficiency gains and investment costs. Such an extension would, however, make a reformulation of the proposed mixed integer linear programming approach necessary.

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