Fuel Substitution Options in the Electricity Sector - The Dependency on Capital Malleability

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Abstract

In economic models a common approach to the description of technological relationships between input factors is the use of neoclassical production functions. This type of production function is based on the assumption that the switch from one input combination to another is not restricted. Changes in the input combinations are mainly caused by changes in relative prices. Putty-clay effects like the dependency of the production possibilities on the existing capital stock or of the technological development on the vintage structure of the capital stock are ignored in most of the models. From an engineering point of view doubts are stated about the ability of this approach to describe the technological options for input factor substitution in a realistic way. It is argued that load factors as well as the dependency of the use of fuels and other materials on the development of the capital stock have to be taken into account. For example, the electricity sector shows that a considerable substitution of inputs is only possible if there is a need for replacement investments i.e. new power plants. Thus, taking into account technical restrictions and the fact that excess capacity in the different load areas is limited, a given power plant stock provides only a marginal ability to switch substantially from one kind of fuel to another – at least as long as there is no need for the replacement of whole plants. The possibilities to change the fuel mix - allowing for technical constraints, the vintage structure of the power plant stock etc. - can be assessed by using the results of energy system models. Such a model is used in the following. The aim of this paper is to point out ways to improve the technological foundation of production functions in economic models. The paper aims at ensuring increasingly realistic results based on applied energy economic modeling and, hence, at an improved robustness of policy recommendations.

1 Introduction

In recent years a lot of new economic models have been developed to analyze climate change mitigation strategies and the effects such strategies have on economic and technological developments. These models usually use neoclassical production functions to describe technological relationships between different kinds of fuels and between fuels and other input-factors. Technological aspects like vintage structures, load and availability factors and their influences on the structure of the fuel mix are ignored or only be taken into account in a very aggregated way. So such an approach may not reflect the options for fuel substitution, and therefore the cost for CO_2 mitigation strategies, in an appropriate manner.

To be able to assess potentials for fuel substitution it is necessary to take a closer look at technological structures. Very detail information about different kinds of energy conversion, distribution and end-user technologies, about availability of resources and the interactions between the technologies, different kinds of technological constrains and the vintage structure of the capital stock can be assessed by using the results of energy system models. In the following we will use an example of this kind of model to identify potentials and costs of fuel substitution options in the electricity sector. The aim of doing this is to point out ways to improve the technological foundation of production functions in economic models. The results should help to increase accuracy of applied energy economic modeling and, hence, improve the robustness of policy recommendations.

2 Methodology

In the next paragraphs we present the methodology which will be used to assess the potentials and costs of fuel substitution options focusing on the possibilities for coal-gas substitutions in the electricity sector. We will start our explanations with some preliminary remarks. Afterwards we will describe the energy-system model which we will use to identify the fuel substitution options.

2.1 Preliminary remarks on costs and potentials of fuel substitution options

- *Costs of fuel-substitution options*

The example of the historical development of the fuel mix used in the EU for the production of electricity shows that the structure of this mix has changed significantly over time (IEA

2003). In the past the development of the fuel mix has been influenced by a lot of different factors: changes in the fuel prices, technological progress and political constrains might be the most important factors. Also the importance of the vintage structure of the power plant stock has to be stressed at this point: With an increasing age power plants had become less profitable. If they reached the status of uneconomic they had been phased out and replaced with new ones.

To assess how the fuel mix will look like in the future and what are the potentials resp. costs of options to influence the development of the fuel mix it is necessary to distinguish between

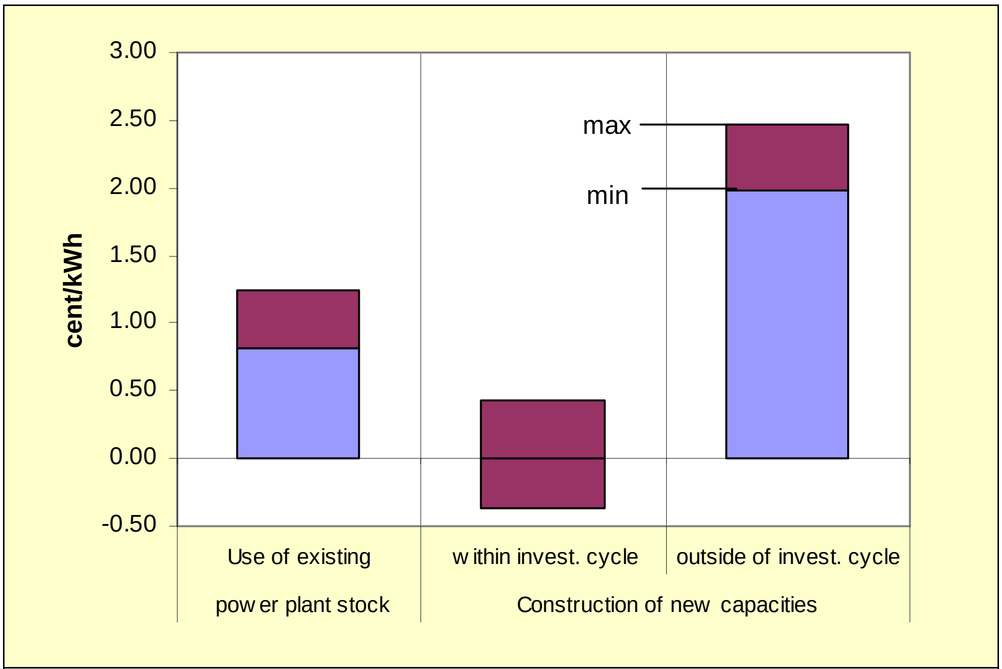
- the fuel substitution options an existing power plant stock offers,
- possibilities to influence the mix by putting new plants into operation.

In the second case it is necessary to make a distinction if there is a need for new capacities or if the new capacities leads to excess capacity.

Figure 1 shows an example of the costs of the different kinds of options for fuel substitution. In the example it is assumed that using more gas for the production of electricity should reduce the share of coal in the electricity production.

The additional costs of a simultaneous increase in the output of gas-fired power plants and decrease in the use of coal using the existing power plant stock, lead in dependency to the fuel prices to additional costs of approx. one cent/kWh. In this case only the variable costs (incl. fuel costs) of the different types of power plants have to be considered in the cost calculations.

In second case ('Construction of new capacities within the investment cycle') the costs of fuel substitutions have to be calculated by comparing total costs (variable and fixed costs incl. capital costs) of each kind of power plant type. The total costs of gas and coal-fired power plants do not differ very much, so the additional costs of fuel substitution are very low. Even they could fall below 0 if low fuel prices and low load factors are assumed.



Notes: Own calculation based on data of Enquete-Komission (2003), max. and min. costs are estimated by variation of the load factor and fuel prices

Figure 1: Costs of different options for a substitution of gas for coal

The costs will be significantly higher if new gas-fired power plants are built and used to produce electricity without any 'real' need for new ones, because in this case excess capacity is created which will lead to additional costs. In our example the costs rise up to 2.5 cent/kWh.

So the cheapest way to change the fuel mix is to use the options investment cycles offer. Measures for fuel substitution using the existing power plant stock are more expensive but compared with the costs of constructing new power plants outside the investment cycle they are still low.

- Potentials for fuel substitution

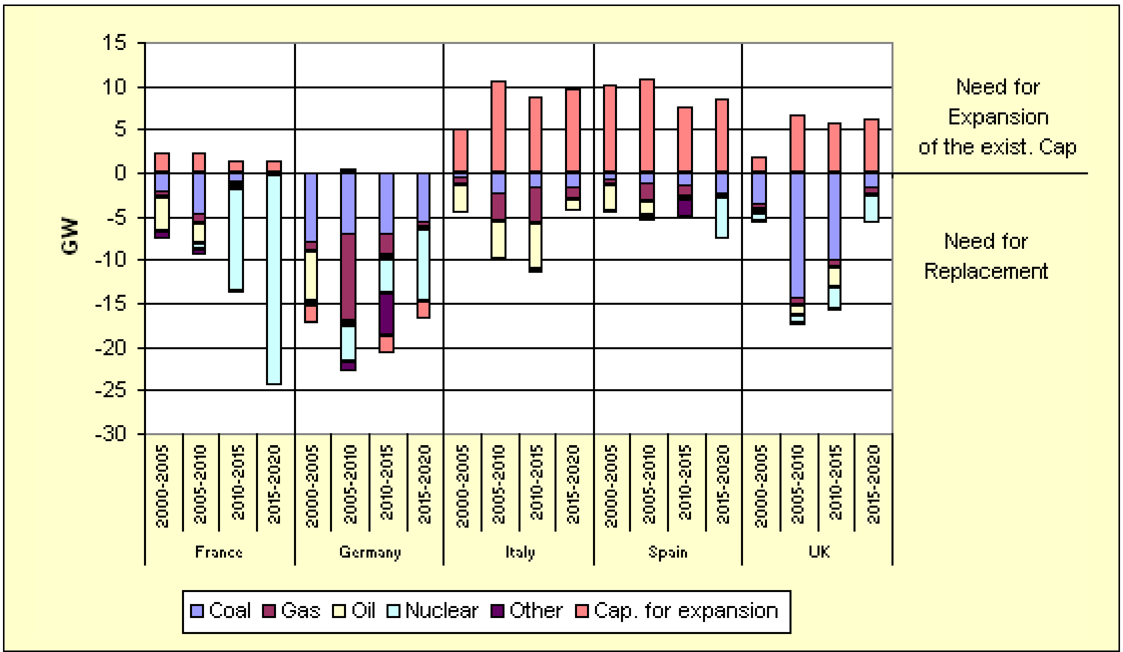
In the following we want to analyze the potentials for the different options for fuel substitution focusing on the possibilities for coal-gas substitutions.

To assess the potential for fuel substitution by using investment cycles, information about the development of the total demand for capacity and the development of the remaining power plant stock is necessary. Examples of this are presented in Figure 2. The first example shows the electricity sector of France: It is expected that in France the demand for electricity and therefore the demand for the total capacity will increase up to 2020 slowly. (Eureletric 2002) In principle the gap between the demand of one period and the demand of the period before can be filled by putting new coal-fired power plants into operation as well as by switching on new gas-fired plants. Taking into consideration that in the first two periods only a few power plants will reach the end of their lifetime, in the short term there will be a small need for replacements. Especially in the second period old coal-fired power plants will have to be replaced. If you replace them with new gas-fired power plants the share of gas in the electricity mix will increase. Meanwhile, due to the phasing out of the old coal-fired plants and the construction of new gas-fired power plants instead of replacing the old plants with new coal-fired power stations, the share of coal will drop. Assuming a lifetime of 40 years for nuclear power stations, after 2015 the need for new power plants will rise significantly. In principle, each of the different power plant types can be used to close this gap. However, it is very likely that for political and strategical reasons the old nuclear power stations will be replaced with new ones. Therefore the 'real' options for changing the fuel mix during these periods will be limited.

Especially in Germany the demand for new power plants is driven by replacement needs. In the short term, a lot of gas-fired power stations built in the seventies will have to be replaced. If they are not replaced with new gas-fired power plants, the share of gas will decrease. In this case it is likely that the share of coal will increase. On the other hand in every period approx. 7 GW of coal-fired plants will have to be replaced by new power plants. This opens the door to switch at low costs gas for coal.

In contrast to France and Germany it is expected that in Italy and Spain the demand for electricity will increase significantly. However, in this countries there will be only a small demand for replacements. The sum of demand for expansion and replacement will offer a high potential to increase the share of gas in the electricity mix at low costs.

In the UK a lot of the existing coal-fired power plants will soon reach their end of lifetime. Therefore especially in the second and third period there will be a significant potential for fuel substitution. Figure 2 shows that in the medium term there will be a lot of capacity gaps, which can be filled by putting different kinds of new power plants into operation. However, it has to be stressed that once one gap is filled for the next years there will be no cheap way back.



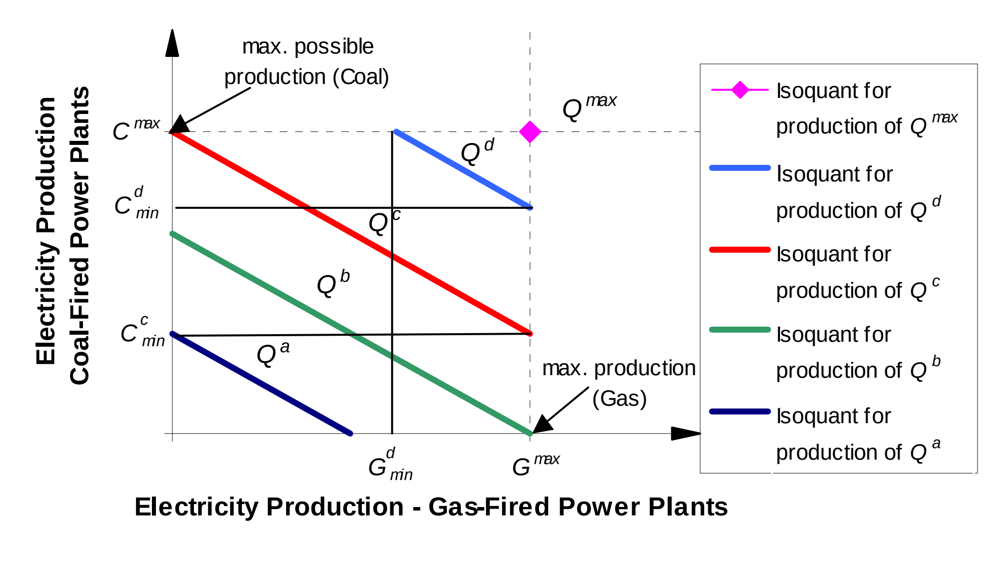
Notes: For information about the data and the approach used for the calculation of the figures see Markewitz/Vögele (2003)

Figure 2: Need for new capacities

Figure 3 illustrates a small, in comparison to Figure 2 more theoretical, example of the limitations of fuel switching in the electricity sector assuming no new power plant is built. In this example there are only two different types of power plants: coal and gas-fired fired power plants. With the existing stock of coal-fired power plants it is possible to produce a maximum of C^{max} of electricity and with the gas-fired power plants G^{max}.

In the example we assume that $G^{max} < C^{max}$. So an amount of G^{max} or less electricity can be produced by using only one type of power plant as well as by using a mix of them. In order to produce more than G^{max} of electricity at least one part of the demand has to be generated with coal-fired-power plants. The colored lines in Figure 3 shows all possible options to produce a specified output. After reaching a maximum at Q^c, the lines become shorter which means that the possibilities to switch between the different types of power plants decrease as the demand for electricity increases.

The maximum output (Q^{max}) can only be produced with one combination of power plants: In this case both types of power plant are used at their maximum level. So at this output level a substitution of the different types of power plants is not possible.



Notes: $C^{c}_{\min}$: minimum utilization of coal-fired power plants to produce Q^{c} electricity

$C^{d}_{\min}$: minimum utilization of coal-fired power plants to produce Q^{d} electricity

$G^{d}_{\min}$: minimum utilization of gas-fired power plants to produce Q^{d} electricity

Figure 3: Example of possibilities for fuel substitution

In real life the maximum production of one type of power plant is not only limited by the amount of the existing capacities but also by technological restrictions like the degree of availability and the need to have excess capacity to ensure a safety energy supply. Taking into account that the utilities want to maximize their profits and do not want to have more excess capacity than necessary, the possibilities for fuel substitution using only the existing power plants are very limited in the short-term.

Besides the possibilities the existing power plant stock offers and the option to use the need for new power plants for cheap changes in the electricity mix there is as a third option: The mix can be changed by putting on new power plants outside of investment cycles. In principle the potential for this option is unlimited.

2.2 The IKARUS-MARKAL Model

The different kinds of options to change the fuel mix and the interactions between them -allowing for technical constraints like the vintage structure of the power plant stock etc. - can be assessed by using the results of energy system models. An example of such a model is IKARUS-MARKAL, which was developed within the IKARUS-Project to describe the energy flow from the primary energy sector to the energy end-use sectors industry, transport, households and small-scale consumers in Germany (Hake 1998, Martinsen et al. 2003). IKARUS-MARKAL is a process-based optimization approach of the Linear Programming type, representing (bottom-up) energy technologies along the energy conversion chains (Fishbone 1983). Assuming perfect foresight the model minimizes the net present value of the energy system throughout the planning horizon. The model contains detailed information about costs and technical aspects of more than 500 different technologies: Beside data on investment and operating and maintenance costs, there is data on technical lifetimes, availability factors and emission coefficients for each technology. Taking into account exogenously given fuel prices, the levels of production activities, constraints on penetration of new technologies and emission targets, the model delivers information about the cost-optimal mix of technologies to satisfy the assumed useful energy demand. Apart from a lot of other detailed information, the model provides data on the optimal mix of technology for the electricity sector. The mix of technology in this sector depends on the development of fuel prices as well as on the costs of the different technologies, on the vintage structure of the capital stock, technical aspects (e.g. load factors, the need for back-up capacities [especially for wind power plants]), the availability of resources, the structure of the demand for electricity and policy constraints. Therefore all the different kinds of options for fuel substitution are taken into account automatically. Changes in the prices of one type of fuel for example will lead to an increase in the use of other kinds of fuels if the costs of using these fuels in power stations are lower and if there are no constraints which limit the substitution options. Changes in fuel prices will also influence the decision which kind of new power plants should be built if there is a need for new capacity. If the event of extremely high fuel prices, it is possible that new, more efficient power plants will be built even if there is no technological need for new ones.

Table 1 shows some key indicators which we used in our calculations.

Table 1: Key indicators

	Unit	2000	2010	2020	2030
Population	Mio.	82.0	81,5	80.3	78.0
Number of households	Mio.	37.5	38.5	38.8	38.1
Average household size	Persons	2.19	2.12	2.07	2.05
GDP	Mrd. € (95)	1963.8	2366.7	2797.5	3189.6
Lignite - Mining	PJ	1 521	>1 400	>1 400	> 800
Wind (installed capacity)	GW	5.9	> 19	> 25	> 35
Nuclear power (installed capacity)	GW	22.2	18.3	7.8	0

The calculations are based on the assumption that the population of Germany will decrease significantly in the long-term whereas an average increase in the GDP of 1.8 to 2 % is assumed. Beside assumptions about population trends and economic growth, a large number of other assumptions are also taken into account. Regarding the technological development of the electricity sector the assumptions about the development of wind energy and the use of nuclear power have to be stressed. For example in case of wind energy the current trend for wind energy which anticipates still a strong increase is taken into consideration. According to the agreement about phasing out the peaceful use of nuclear power reached by the Federal Government and the nuclear power station operators, the phasing out will be completed after a quantity of 2.623 TWh have been produced, which corresponds to approx. 33 years for each power plant. Very important for the calculations are assumptions about fuel prices. The prices for fossil fuels, which are used for the following calculations, are presented in Table 2.

Table 2: Fuel prices

	€/GJ		
	2000	2010	2020
Hard coal	1.32	1.76	1.80
Lignite	1.44	1.51	1.64
Crude Oil	5.32	4.39	4.49
Gasoline	7.06	6.28	6.51
Diesel	6.95	5.45	5.61
Light fuel oil	6.95	5.45	5.61
Heavy fuel oil	5.06	3.51	3.60
Natural Gas A	3.27	3.65	3.82
Natural Gas B	4.11	4.56	4.77

In the following we will use the IKARUS-MARKAL model to show the potential and limitations for fuel switching in the electricity sector.

3 Results

To identify the potential of fuel substitution options we start our calculations assuming steady prices for hard coal and gas. In the next runs an exponential increase up to a specified level in the prices of hard coal and gas is assumed.

The results of the first run are presented in Figure 5. This figure shows that even if coal and gas prices remain unchanged the fuel mix of the electricity sector will change significantly. The development is mainly driven by the vintage structure of the power plant stock and the decision to phase out nuclear energy within the next 20 years.

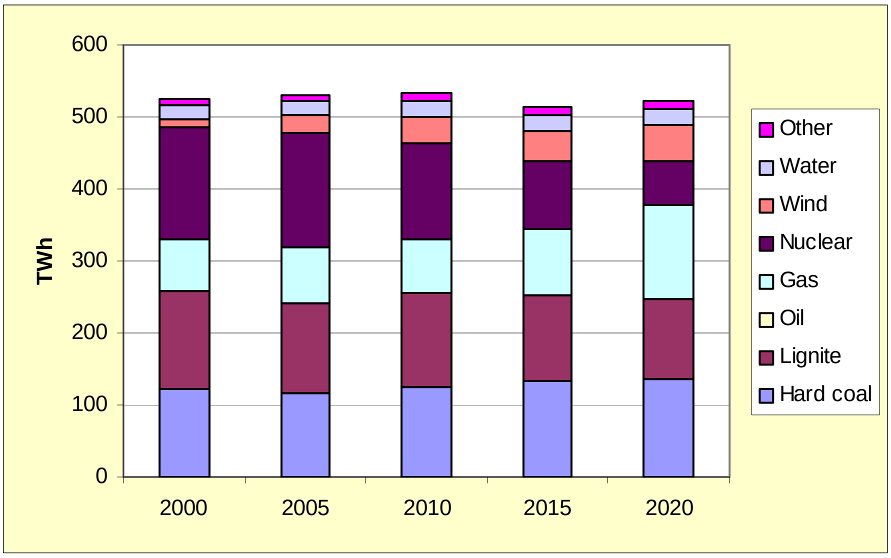


Figure 4: Development of electricity production (constant fuel prices)

In the short-term an increase in the gas price will only have small effects. In the ‘worst’ case scenario (a 40% increase in the gas price and unchanged prices for hard coal) the share of gas will drop by 10%. In the ‘best’ case (steady gas price and a 40 % increase in the price of hard coal) the share will rise by 8 %. The results for coal are similar. Changes in the coal and gas prices induce only variations of the output of the coal-fired power plants of –6 % to 10 %.

However, in the long-term the same changes in the prices (compared to 2000) lead to significantly different results. Assuming constant fuel prices, the production of electricity from using gas will rise to 134 TWh. In comparison to 2000 this means a growth of 94 %. A 10 % increase in the gas price will result in a sharp drop to 81 TWh. The production will decline to 75 TWh if further increases in the gas prices are assumed.

With high coal prices the use of gas-fired power plants becomes more profitable: In the event of high coal and steady gas prices, the production will rise to 170 TWh. In the scenario ‘Price of coal +40 %’ the use of gas for the electricity production will remain almost unchanged provided increases in the gas prices amount to less than 11 %. With higher gas prices the production will decline sharply to 85 TWh. This limit is reached at the level ‘Gas price of 2000 plus 24 %’. After that further increases in the gas prices leads only to small changes in the use of gas-fired power plants.

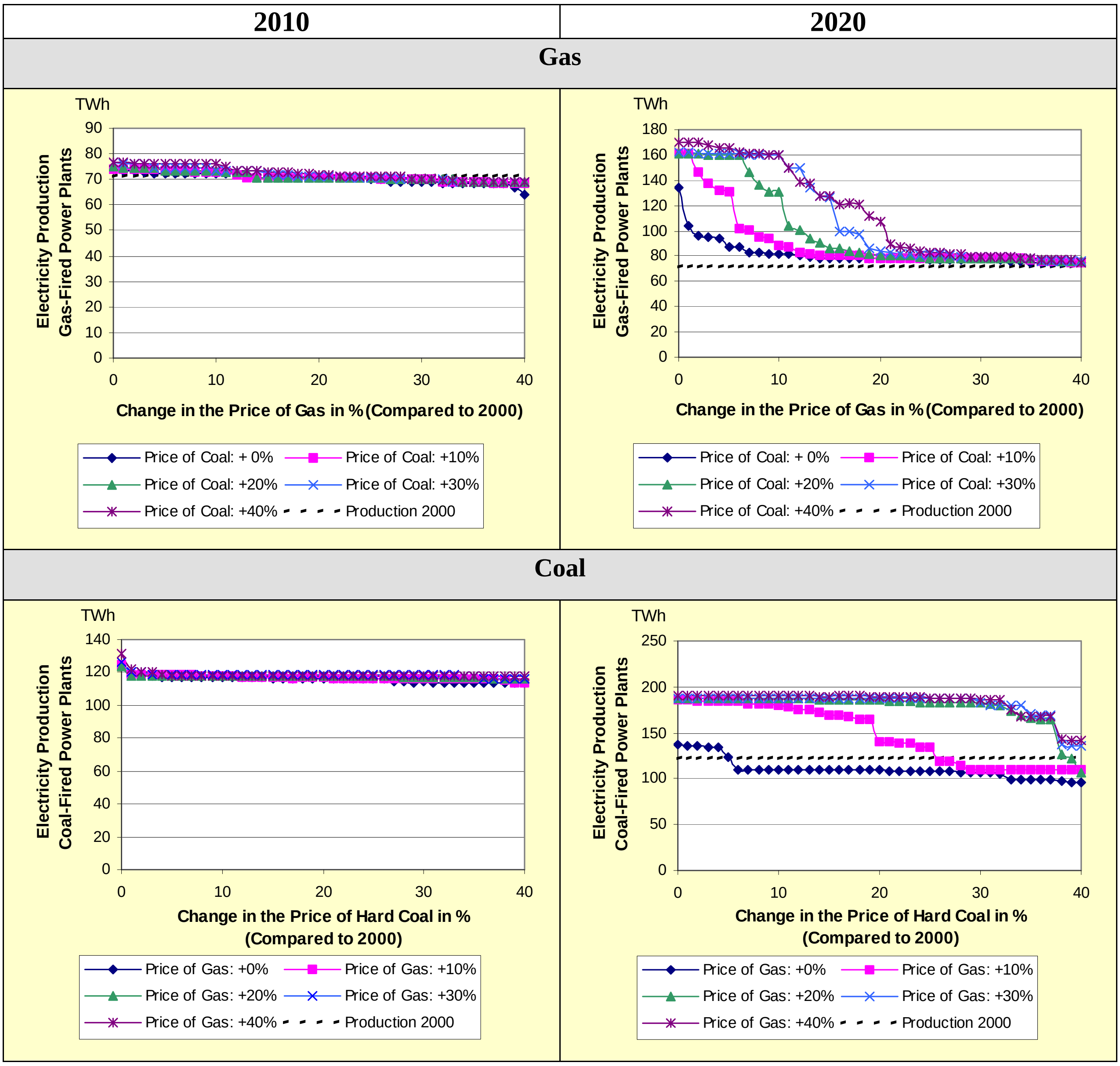


Figure 5: Electricity production - Variation of fuel prices

In the other scenarios with lower coal prices ranges of more or less stable shares of gas in the total electricity production and a range of a sharp decline can be identified. In each of scenarios the range of the sharp decline is limited to 10 to 15 points.

In principle, the share of the sum of gas and coal in the total is constant in all scenarios. Only in the high price scenarios the share of other fuel increases significantly. (Figure 6) So in general the development of use of hard coal for electricity production reflects the inverse one for gas.

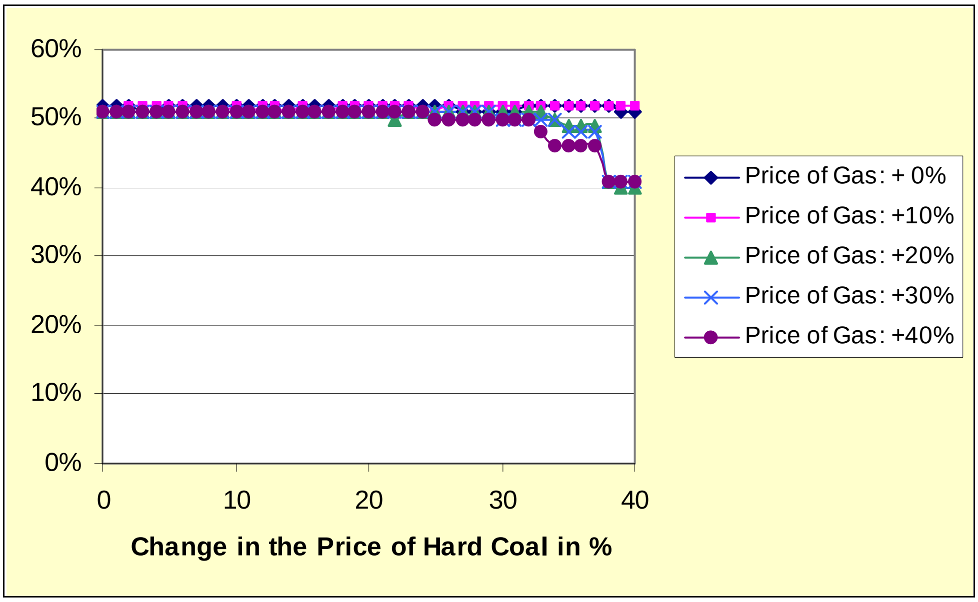


Figure 6: Share of the sum of gas and coal in the total electricity production (2020)

The employed approach also exhibits the direction and magnitude of the development of the relative use of fuels respectively the dependency of coal and gas use on relative changes in fuel prices for the years 2010 and 2020 and, hence, gives a first impression of the difference between short- and long-term price elasticities.

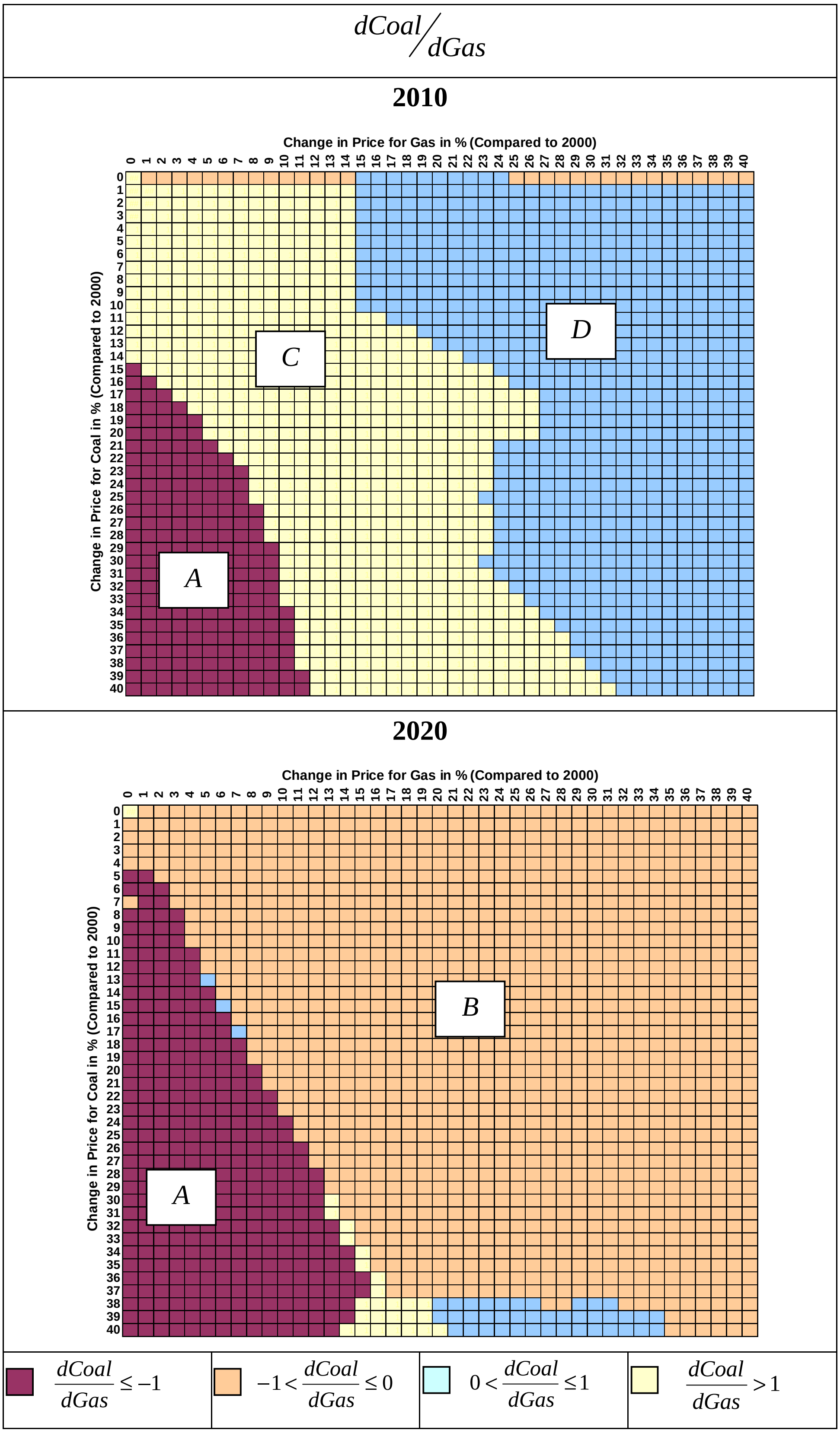


Figure 7: Direction and magnitude of fuel substitution possibilities

In Figure 7 *dCoal* and *dGas* denote the changes in the shares of coal and gas use in the total electricity production for the years 2010 and 2020 compared to the development with constant prices. The dark areas *A* and *B* in this figure show the situations at which the use of one of the fuels gas or coal decreases and the other one increases. *A* shows the combinations with higher changes in coal than in gas and *B* the ones with larger changes in gas than in coal. Less gas and less coal are used in the areas *C* and *D*. *C* reflects the situations with higher changes in use of coal than in the use of gas and *D* the ones where the decrease in the use of coal is smaller than the drop in the use of gas.

The figures for 2020 are dominated by combinations of type *B*. This indicates that in general changes in prices lead to an increase of one type fuel and a drop of the other one whereby the use of gas is more sensible to changes in the prices than the use of coal.

The results for 2010 are different to the ones of 2020: Instead of increasing one fuel and decreasing the other one in the most cases changes in prices lead to a reduction of both types of fuels. This reflects the limited possibilities for substitutions in the short-term.

4 Conclusion

In this paper we stress the possibilities of changing the fuel mix in the short and long-term using the example of the German electricity sector. Three different ways to change the fuel mix have been identified: The cheapest one is to use the 'windows of opportunity' investment cycles offers. This option depends on the development of demand for electricity and the vintage structure of the capital stock. A more expensive way to change a fuel mix is to use the existing capital stock. Because the utilities want to maximize their profits and do not want to have more excess capacity than necessary, the possibilities for fuel substitution using only the existing power plants a at a given point in time is very limited. The most expensive option for fuel switching is to build new power plants although there is no 'real' need.

In the case of the German electricity sector in the short-term (up to 2010) cheap possibilities to replace coal with gas are very limited due to small 'windows of opportunity'. After 2010 the replacement demand for coal-fired power plants will be quite high, so in the long-term an increase in the share of gas in the electricity production could be achieved at low costs.

To assess the options for fuel substitution, and therefore the cost for CO_2 mitigation strategies, in an appropriate manner, it is advisable to link the use of fuels to the development of the capital stock. We also recommend using different elasticities for short- and long-term analyzes.

5 Literature

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