February 1989. Paper to appear in System Dynamics Review 6 (no.1 Winter 1990): 44-65.

Interfuel Substitution in OECD-European Electricity Production

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ABSTRACT

Fuel substitution in OECD-European electricity production is described by a putty-clay formulation. At the time of investment, fuel shares are determined according to a logit model. These fuel shares are maintained throughout the lifetime of the power plants. However, a significant share of capacity is assumed to be flexible. Short-term fuel switching is described by a logit model. An attempt has been made to formulate the model such that all parameters have a real life interpretation. This enables the use of a priori data about all parameters. The model gives a very good fit to historical time-series for oil, gas and coal demand when fuel premiums are calibrated. The most striking finding is that there is a strong preference for the use of coal. Because of the a priori data, the model is not very sample dependent. Thus, it should be well suited for policy studies or for predictions. The model should be used with caution if very high fuel prices are expected.

Introduction

The potential for interfuel substitution in electricity production is clearly very large since electricity can be produced by any of the fossil fuels oil, gas and coal, as well as by hydro and nuclear power. Our focus is on the fossil fuels oil, gas, and coal. Which fuels producers choose, depend on the relative costs of the alternatives. Since different producers in different regions face different costs, it is likely that all fuels will be chosen to varying extents. One purpose of this paper is to investigate how much of the different fuels are chosen for different underlying costs. We also aim at disclosing eventual preferences for the fuels.

A second purpose is to investigate the adjustment dynamics. A priori we know that life-times of power plants are about 30 years. There are considerable costs involved in converting a plant from using one fuel to using another. And, about 30 percent of capacity is flexible with respect to short-term fuel choice. We want to find out if these a priori data are consistent with historical development.

For both purposes, a simulation model of interfuel substitution is developed. A multinomial logit model is used to determine fuel shares both in new power plants and in the utilization of flexible capacity. The dynamics of "inflexible capacity" are captured by three vintages, one for capacity under construction and two for operating capacity. Thus, we have chosen a putty-clay model. The model only explains substitution between fuels. Total demand for electricity is exogenous to the model as it is to power plants.

At the outset, the model might seem more complicated than regular econometric demand models. We recognize that in general complexity is no guarantee for improved performance, see for example Armstrong(1985, p.227-232), Granger and Newbold(1977, p.290), and Zellner(1984, p.7) who refers to Jeffreys-Wrinch simplicity postulate and Ockham´s razor. Our intention, however, is to present a model that is more closely related to reality and real-life information than the ordinary constant elasticity models. Hopefully the reader will find the model to be "sophisticatedly simple" in the words of Zellner. To explain this term, he refers to a "complicated" model as one which is not well understood.

To estimate parameters we will rely heavily on a priori data. In line with Bayesian theory, only the most uncertain parameters will be adjusted to improve the fit between simulated and histori-cal behaviour. These are the parameters pertaining to preferences.

The simulation model replicates historical development in OECD-Europe from 1960 to 1983 amazingly well. The most remarkable finding when calibrating the model is a strong preference for coal. Flexible capacity is demonstrated to improve the fit considerably. The good fit shows that an average adjustment time of about 20 years is consistent with history.

First the simulation model is discussed. Next data for electricity generation in OECD-Europe are presented. Then model behaviour is discussed and parameters calibrated. Finally, a number of other experiments with dynamic logit models are reported, and the model is compared to two other models of substitution. All prices are in 1983 USD.

A Simulation Model of Interfuel Substitution

Fuel demand from the electricity generating sector of OECD-Europe depends on fuel substitution, efficiency in the generating process, and demand for electricity. We consider the latter two factors exogenous. Our model of interfuel substitution involves the following five steps:

- determining fuel shares in power plant investments
- keeping track of vintages of power plants
- determining total investments in power plants
- determining capacity utilization of power plants
- determining the utilization of flexible capacity

Determining Fuel Shares in Power Plant Investments

Numerous factors are likely to influence the choice of fuels in new power plants. We will focus on standard cost elements, and lump the rest together in a fuel premium. Total costs C_i of fuel option i is given by the formulae:

$$C_i = CC_i / PBT + OO_i + FP_i / E_i - P_i \quad (1)$$

CC_i is capital costs, PBT is required payback time, OO_i is other operating costs than fuel costs, FP_i is the fuel price, E_i is the burner efficiency, and P_i is a positive or negative premium. The premium reflects concerns about domestic employment opportunities, cleanliness, flexibility, availability, and national import dependence on the fuel. Some of these concerns might be formalized in terms of laws and regulations, others might show up in terms of directives and hidden subsidies. When P_i is calibrated to make the model fit historical behaviour, the premium will also reflect errors in parameter estimates and deficiencies of the model.

All cost elements in equation 1 vary from plant to plant. Capital costs vary due to different requirements at different sites, and because a multitude of equipment suppliers offer different prices. Burner efficiencies, other operating costs, payback time requirements and premiums vary similarly. Fuel prices vary between fuel qualities and between countries. Different tax regimes and regulations explain much of the latter variation.

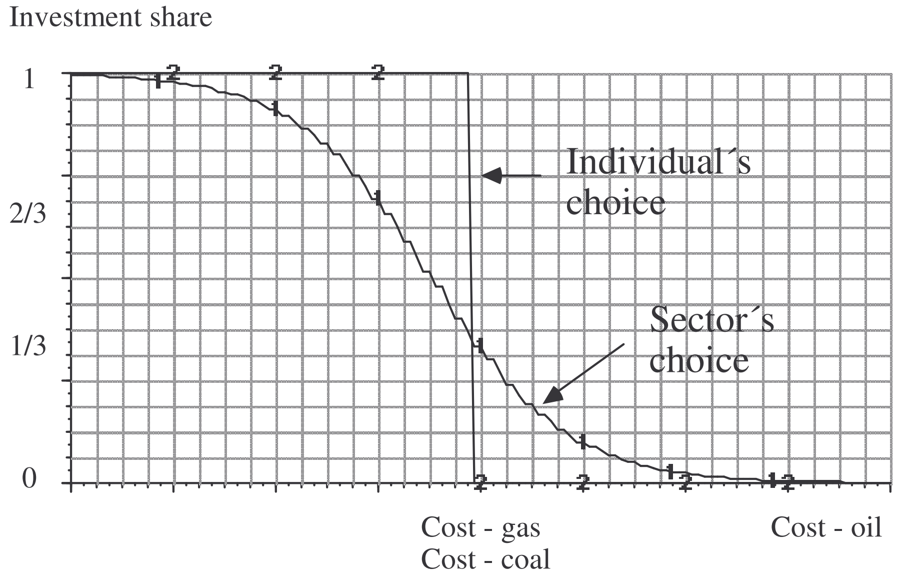

Figure 1: Investment share for oil in new power plants as a function of the costs of using oil, costs of gas and coal are fixed in this illustration.

To describe the fuel choice we apply the multinomial logit model. We give a popular descrip-tion of this model before we turn to its properties. For the individual plant the choice is typi-cally one or another of the options. The model assumes that the individual producer chooses the cheapest alternative. This is illustrated by the straight lines in figure 1. When the total costs for oil are below the costs of the alternatives gas and coal, oil is chosen. When the total costs of oil are not the lowest, one of the other fuels is chosen.

The fact that different users face different total costs, implies that the sum of users behave differently than the individual user. All users will not suddenly shift from oil to gas or coal when the *average* costs of oil increases slightly above the average costs of gas and coal. Some of the users will still find oil to be the cheapest alternative. The smooth and curved lines in figure 1 show how the market share is gradually lost as the average total costs of oil increase. This is a less rigid view of the substitution process than what is implied by the popular assert-ion that a fuel is either competitive or not competitive.

The multinomial logit model (MNL) for planned fuel shares PS_i is shown in equation 2:

$$PS_i = \frac{e^{-\alpha C_i}}{\sum_j e^{-\alpha C_j}} \qquad (2)$$

The MNL has only one parameter α, except for the parameters that enter the cost function in equation 1. When costs are given, α determines the steepness of the curve in figure 1. When α is at a high extreme the function mimics the individual´s choice. In the MNL the sum of market shares always add up to 1. When all costs are equal, the market is split in equal shares. The latter property is not very important since fuel premiums change costs. If we divide numerator and denominator of the logit function by exp($-\alpha C_i$), we see that fuel shares depend on cost differences.

The MNL belongs to the class of random utility models. In our case utility is expressed through costs, which are distributed independently according to the Weibull distribution. Quarmby(1967) has derived the MNL by discriminant analysis, and has showed that an expression with cost differences minimize misclassification[1]. The derivation bears on Luce's axiom which states that relative probability of choice is not changed by one extra alternative, Luce(1959). Wilson(1967) has derived the MNL from maximization of entropy. Finally McFadden(1973) derives the MNL from utility maximization, where he introduces the Weibull distribution. He shows that $\alpha^2=\pi^2/6\sigma^2$, where σ^2 is the variance of the Weibull distributed costs. This relationship is helpful in gaining a priori information about the parameter α. Finally, we can show that the own-price elasticity of a fuel share is $\varepsilon_{ii} = -\alpha(1-PS_i)FP_i/E_i$, and the cross-price elasticity is $\varepsilon_{ij} = \alpha PS_j FP_j/E_j$. Note that the absolute value of the own price elasticity increases with own price, and it decreases with own planned fuel share. Actually, since PS_i is a function of fuel prices, we see that each price elasticity is a rather complicated function of all fuel prices. The total effect of own price on own-price elasticity is in the same direction as the partial effect.

Since electricity can be produced by a multitude of fuels, the MNL should be an ideal descrip-tion of substitution. However, a few caveats should be mentioned. Power stations produce both peak power and base load. Daily variations are most easily produced by stations that can be started and stopped on short time notice, stations with low capital costs and high operating costs. This gives a positive premium to gas-turbines using light fuel oil. Gas-fired turbines are less suited since they rely on peak-valued gas supplies or expensive local inventories. Coal and nuclear power stations are both inflexible, and they have both high capital costs and low oper-ating costs. The premium on oil should be expected to drop as the market share for oil expands beyond the level needed for peak power supply only. Over time an increasing share of nuclear power for base load production, implies increasing likelihood of positive premiums on peak load fuels.

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[1]We have experimented with a formulation using relative costs, and have found nearly similar results to those we obtain by using cost differences in this paper. The relative cost model can be expressed as follows:

$$PS_i = C_i^{-\alpha} \sum_j C_j^{-\alpha}$$

The nice thing about this model is that for the case of two fuels, the parameter α is identical to the familiar elasticity of substitution. This indicates a close relation between the MNL and a frequently used model in economics.

A national policy to diversify sources of energy supplies should also imply that premiums increase with falling market shares.

We have excluded nuclear energy from the study, because of lacking data on historical cost development. This means that it is difficult to establish a proper premium on nuclear energy. And, it is not likely that the premium has been stable over the infant years of the technology. One reason for this has been the limited availability of the technology. If a fuel option is not available to all decision makers, those without the option would treat it as "very expensive". The Weibull distribution no longer applies. Clearly, this makes it difficult to estimate a repre-sentative cost measure for the fuel option from a priori data[2].

The actual fuel share in new plants is given as a lagged version the planned fuel share, see equation 3. The average delay time CT reflects the construction time of new power stations. Thus, we assume that the fuel choice cannot be changed after construction has started. Equation 3 represents the first vintage of the putty-clay model.

$$dS_i /dt = (PS_i - S_i)/CT \qquad (3)$$

Total investments I_i in power plants using fuel i are given by the product of fuel share S_i and total investments I.

$$I_i = S_i \cdot I \qquad (4)$$

The model could be simplified by disregarding investments. Planned market shares for the fuels could simply be delayed by construction- and lifetimes of power stations to give actual fuel shares. Fuel demands would be calculated as the product of fuel shares and total demand for energy. An example illustrates way we have chosen to include investments. Assume that coal had a high fuel share in 1960, that the oil price dropped low enough so that no new plants would choose coal, and assume that total electricity demand grew rapidly. In this situation the simplified model would predict the market share of coal to drop slowly, while demand for coal could rise due to the rising demand for electricity. By explicitly modeling investments, we avoid that coal demand increases in case of rapid growth in energy demand.

Keeping Track of Vintages of Power Plants

[2]Nuclear power is included as a fourth fuel in the substitution model in Moxnes(1986c). When assuming that costs are constant and equal to cost estimates for the early 1980s, estimated premiums increase from -$200/toe electricity in 1960 to +$350/toe electricity in 1980. The early negative premiums reflect that nuclear power was not available at 1980-costs in 1960.

New power plants will usually burn the same type of fuel for their whole lifetime. This is because rebuilding or premature replacement is costly and cumbersome. Chessire and Robson (1983, figure 9) show that no premature replacements of industrial gas- or oil-fired boilers with coal fired boilers have a payback time of less than four years. This is for a price differential of 9 pence/Therm between oil/gas and coal, which is about the difference between heavy fuel oil and coal in 1981 (their figure 7). We suspect that the payback times are somewhat lower for large power plant boilers than for industrial boilers. For higher price differentials, a shift between fuels can occur during the lifetime of the plant. This should be kept in mind when using the model with extreme price assumptions.

With the above simplifying assumptions, the dynamics of the model become fairly simple. Two vintages of capital, new capacity KN_i and old capacity KO_i are kept track of. Investments I_i increase the stock of new power plants. Aging of new power plants DN_i redefine new capacity into old after half the lifetime of the power plants LT. DO_i is the scrapping of old power plants. Capital is defined in units of capacity to burn fuels (Mtoe/year).

$$dKN_i/dt = I_i - DN_i \tag{5}$$

$$dKO_i/dt = DN_i - DO_i \tag{6}$$

$$DN_i = KN_i/(LT/2) \tag{7}$$

$$DO_i = KO_i/(LT/2) \tag{8}$$

Aging of new and old power plants is proportional to the number of power plants in each category. This means that a fairly wide distribution of lifetimes is implicit. Using two vintages ensures that no power plants are depreciated immediately after investment. Lack of more precise data about the lag structure is not terribly important since the behaviour of the model is relatively insensitive to the number of vintages.

Determining Total Investments in Power Plants

Since we have no data on investments in new capacity, capacity additions are estimated from total energy demand in the sector. A simple way to do this is to let total yearly investments be equal to scrapping of old plants plus the difference between historical demand and simulated capacity in each year. However, this formulae has a weakness if demand drops rapidly, because investments might then become negative. In reality, rapid demand reductions are accommodated by reductions in capacity utilization or by premature scrapping of old capacity. Investments will always be greater than zero, because some utilities will need to expand capacity even though the rest may have zero investments. This non-linearity is taken care of in the expression for total investments in inflexible capacity I. A similar non-linearity is used by Sterman(1981, eqn. 93-94).

$$I = \sum_i DO_i f\left(\frac{(1-FF)ED - \sum_i K_i}{TI\sum_i DO_i}\right) \tag{9}$$

ED is the exogenous total demand for energy. 1-FF denotes the fraction of total demand that is met by inflexible capacity. The time to adjust investments TI determines how fast invest-ments adjust simulated capacity towards exogenous demand. The function is normalized by total scrapping of old power plants.

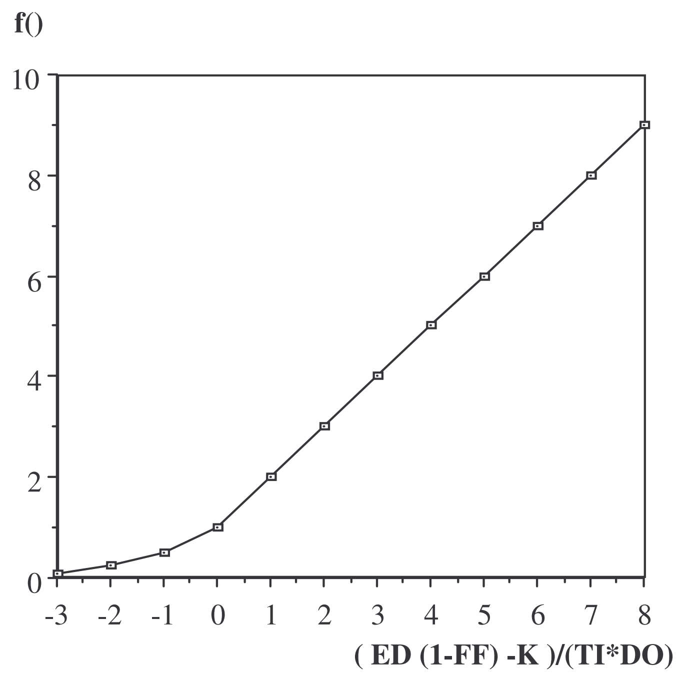

Figure 2: Form of the non-linearity in equation 9.

Figure 2 shows the exact shape of $f(\cdot)$. When capacity equals demand, no adjustments are needed and investments equal scrapping of old plants DO ; $f(0)$=1. As demand falls below capacity, investments will tend towards zero. Since historical data only provide observations of declining total capacity in the three last years, this part of the curve is of no importance when testing the model. Additional a priori information should be considered when making forecasts. When demand is larger than capacity, the relationship allows for full adjustment of the power plant stock.

Determining Capacity Utilization of Power Plants

To track exogenous total energy demand under all circumstances, the notion of capacity utilization is introduced. Capacity utilization U for inflexible capacity is simply calculated as:

$$U = \frac{(1 - FF)ED}{\sum_i K_i} \tag{10}$$

If exogenous demand for inflexible capacity ED (1-FF) drops below simulated total inflexible power plant capacity ΣK_i, utilization drops accordingly. Capacity is not forced down. Thus, the model aims at maintaining a capacity that is sufficient to meet all peaks in demand[3]. This is a much used method for estimating production capacity from production data, the socalled Wharton method.

Capacity utilization is assumed to be the same for all types of fuels in each sector. A possible relationship between capacity utilization and the fraction of total energy demand that is flexible is not captured by the model.

Equation 11 shows the calculation of the demand D_i for each fuel i. DF_i represents demand from flexible capacity.

$$D_i = K_i \cdot U + DF_i \tag{11}$$

Determining Utilization of Flexible Capacity

Some power plants have dual- or multi-firing capacity; they can switch between fuels. In addition, power plants using different fuels are connected to the same grid. Thus, at off-peak hours utilities can increase the load factor of the power plants with the lowest operating costs. The effect is known as "power-wheeling".

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[3]Although the aim of the model is to maintain sufficient total capacity for all demands, it will not do so when there is growth in demand. The same problem exists in reality, and is solved by planning for excess capacity, and by incorporating growth expectations in investment decisions. The model mimics the solution of excess capacity if we redefine capacity and utilization. Time to adjust investments TI can be reduced to narrow the gap between capacity and demand, at the cost of increasing instability.

Operating costs O_i cover fuel costs and other operating costs like in equation 1. The third term PF_i denotes possible premiums attached to the different fuels when used in flexible capacity.

$$O_i = FP_i / E_i + OO_i - PF_i \tag{12}$$

A multinomial logit model is used to calculate indicated market shares ISF_i for the different fuels i. The distribution is characterized by the coefficient β. By using the MNL we assume that all fuel options are available to all decision makers, see comments to the MNL in equation 2. This requirement is not met for flexible production if a fuel has a very low market share for ordinary capacity. In such a case, power wheeling would be ruled out for this fuel. Thus, we suspect that fuel premiums for flexible capacity are functions of market shares for inflexible production. This should be kept in mind when the model is used for projections with constant fuel premiums.

$$ISF_i = \frac{e^{-\beta O_i}}{\sum_j e^{-\beta O_{ji}}} \tag{13}$$

The actual market share SF_i lags the indicated market share ISF_i by the average adjustment time TAF. After a price change, time is needed to deplete inventories of the more expensive fuels and to acquire increased deliveries of the cheaper fuels. Minor adjustments of multi-fired capacity might also require some time.

$$dSF_i / dt = (ISF_i - SF_i)/TAF \tag{14}$$

Demand DF_i for fuel i from flexible capacity is given by the total demand from flexible capacity $ED \cdot FF$ times the market share for each fuel. ED is total demand like in equation 9 and FF is the fraction of total demand that is met by flexible capacity.

$$DF_i = SF_i \cdot ED \cdot FF \tag{15}$$

Data for Electricity Generation in OECD-Europe

Three main types of data are used in the model for interfuel substitution. First come the explanatory variables: fuel prices and total energy demand. Then there are the parameters of the model, and finally the initial conditions.

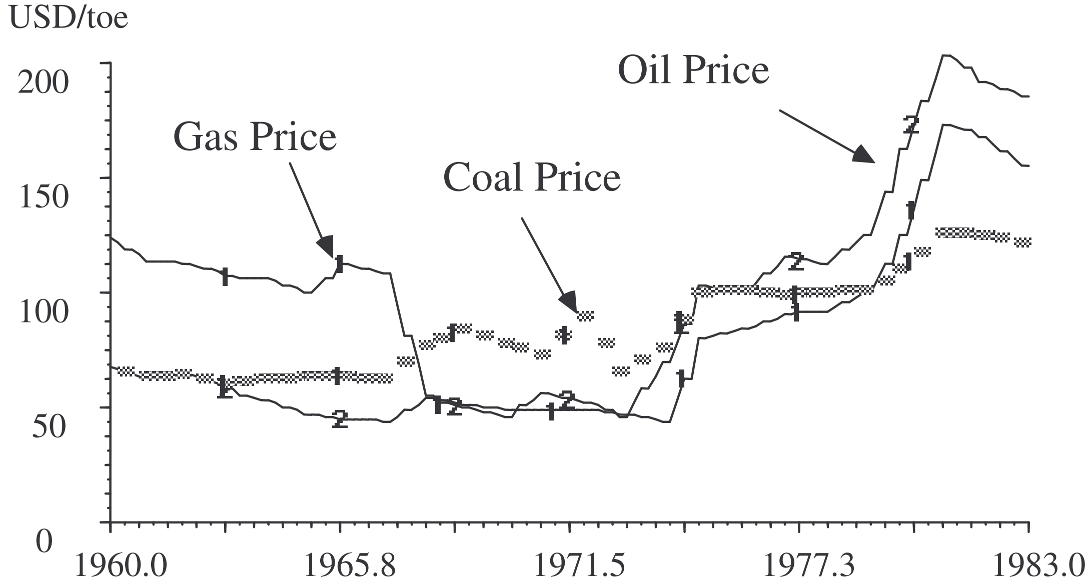

Figure 3: Real fuel prices for the electricity generating sector. Source: Figure 3.3 in Moxnes(1985)

Figure 3 shows how fuel prices to the electricity generating sector have developed from 1960 to 1983. The OECD-European prices shown in the figure are calculate as an average of prices in France, Germany, Italy and the United Kingdom. These four countries made up 64 % of total OECD-European electricity consumption in 1980.

The history of energy prices can be divided into three phases. First is a period when oil and coal were equally expensive while gas was about twice as expensive. In the second period from 1968 to 1973 oil and gas had the same price while coal was about 50 percent more expensive. The third period is characterized by quadrupling oil prices, more than tripling gas prices and a 50 percent increase in coal prices.

Total fuel demand for electricity production for the years 1960 to 1983 is 102, 109, 121, 127, 139, 141, 143, 150, 163, 177, 192, 210, 215, 234, 239, 227, 249, 240, 253, 267, 272, 255, 250, and 244 Mtoe/year, according to OECD Energy Balances. Demand is characterized by rather steady growth except for the last three years.

Table 1: Costs, Efficiencies, and model parameters. Units are in USD/(toe electricity) unless otherwise stated. Sources are mentioned in the text.

	Year	Coal	Oil	Gas
Operating costs	1960	272	237	418
	1970	307	166	176
	1980	417	543	421
	1983	458	614	518
Fuel prices (USD/toe of fuel)	1960	66	68	124
	1970	76	46	49
	1980	108	163	125
	1983	120	185	155
Efficiencies (percent)	all	29	31	31
Other operating costs	all	45	38	38
Annualized capital costs	all	152	113	113
Capital costs (USD/(toe electricity)/year)	all	1520	1130	1130
Payback time (year)	all	10	10	10
Total costs	1960	425	370	551
	1970	460	299	309
	1980	570	677	554
	1983	611	748	651
Lifetime of plants T (year)	all	30	30	30
Parameter for distribution α (toe electricity/USD)	all	0.01	0.01	0.01
Parameter for distribution β (toe electricity/USD)	all	0.015	0.015	0.015
Construction time CT (year)	all	6	6	6
Time to adjust total investments TI (year)	all	3	3	3
Time to adjust flexible capacity TAF (year)	all	0.5	0.5	0.5

Costs, efficiencies and other model parameters are summarized in table 1. Operating costs are the sum of fuel costs (fuel prices divided by efficiencies) and other operating costs. Fuel prices come from Moxnes (1985) p.13. They are defined according to IEA(1984). We suspect that reported coal prices are a few percent higher than actual coal prices[4]. Operating

[4]In IEA(1984) coal prices in Germany and in France only reflect prices of domestic coal. Since imported coal is cheaper than national coal, domestic prices are higher than average prices. In 1982/1983 German prices of domestic coal are about 5 percent higher than the average, and French domestic prices are about 17 percent higher. This means that the average coal price for the entire OECD-Europe in 1982/1983 is about 3 percent too high when we know that Germany consumed about 30 percent of all coal in OECD-Europe and France about

costs, capital costs and conversion efficiencies for coal have been taken from NEA(1983)[5]. Lifetimes of coal fired stations vary between 25 and 40 years. Discount rates vary between 4 and 9 percent per year, see table 7 in NEA(1983). These numbers are used to set lifetimes and payback periods in the model. The construction time of coal fired stations is between 4 and 9 years, see table 7 of NEA(1983).

For oil and gas-fired power stations we rely on sources that give costs relative to the costs of coal-fired power stations, see table 2. The variation of the estimates is quite large. For our purpose, this indicates that variations in capital costs and other operating costs contribute to a wider distribution of fuel choices. As a representative of the average costs we choose the numbers from IEA (1985).

Table 2: Capital and operating costs of oil-fired power stations as percentages of corresponding costs of coal-fired stations.

Source	Capital costs (%)	Operating costs excluding fuel costs (%)
Abbey and Kolstad (1983) (fig. 2)	40	40
Moxnes & Nesset (1985), p. 34 (large industrial boilers)	50	(38 for gas)
IEA (1985), p. 195	74	84
WEC (1983), p. 185 (hypothesis)	83	95

Efficiencies of oil and gas-fired boilers are set according to Moxnes and Nesset(1985), who report that oil and gas-fired industrial boilers are about 7 percent more efficient than coal fired boilers.

Table 1 shows that in 1983 gas and coal fired power stations had almost the same total costs. Higher fuel costs for gas were balanced by higher capital and other operating costs for coal. Oil fired power stations were about 15 percent more expensive than the others due to higher fuel costs.

6.3 percent. We do not know if this tendency applies to the entire historical period. Therefore we have not adjusted the price series.

[5]Operating costs come from table 1 in that publication. The following conversion factors are used: 11700 kWh/toe, 0.924 USD/ECU (table 10), 1.23 1983 FF/1981 FF, 1.08 1983 DM/1981 DM, 1.33 1983 IL/1981 IL, 1.13 1983 PS/1981 PS. Capital costs also come from the same publication. Capital costs have been converted to USD/(toe electric per year) by the above conversion factors and by a payback time of 12.5 years, corresponding to a lifetime of 30 years and a discount rate of 5 percent per year. Both operating costs and capital costs reflect averages for the four major OECD-European countries. Fuel costs and conversion efficiency for coal are found by a combination of tables 1 and 6.

The coefficient for the distribution of investments α is set according to rough estimates of the variation in the different cost elements. The average variation in price differences for fossil fuels between the four major countries in OECD-Europe is USD70/toe. This implies a USD 230/(toe electricity) variation in total costs because of generation efficiencies of about 30 per-cent. In other words, these cost differences extent USD115/(toe electricity) to each side of the mean costs. We use this estimate as our starting point when we assume the standard deviation of the Weibull distribution to be USD128/(toe electricity). This estimate yields a value of α of exactly 0.01 using the formula $\alpha^2=\pi^2/6\sigma^2$.

The distribution of fuel shares for the flexible part of power plant capacity is given by the coefficient β. Since it is only operating costs that enter the logit function for flexible demand, the distribution for flexible demand is more narrow than the distribution for inflexible capacity. The coefficient β is set relative to the coefficient α by judgement.

The time to adjust investments TI is set to maintain relatively smooth investments. The results are not very sensitive to the exact choice of this parameter. Model feedback serves to maintain an appropriate investment rate.

One source we have seen estimates the total dual and multi-fired capacity in electricity genera-tion in IEA-Europe to be about 30 percent of total thermal capacity in 1983. The same source points to the potential for power wheeling. Since most of the flexible capacity is dual, we use a lower percentage for multi-fired capacity than 30 percent, and let power wheeling bring the percentage back up to 30 percent (in 1980). We assume that the fraction of capacity that is flexible increases linearly from 10 percent in 1960 to 30 percent in 1980 and so on. The low fraction in 1960 is explained by insufficient grids and lack of alternatives to coal. The adjust-ment time for the flexible capacity is set equal to 0.5 years.

Table 3: Initial capacities of new and old power plants in 1960. The case without flexibility in parenthesis. [Mtoe/year].

	Coal	Oil	Gas
New plants	48.3 (51.0)	5.8 (9.0)	1.9 (2.0)
Old plants	34.2 (37.0)	0.0 (3.0)	0.0 (0.0)

Initial conditions are obtained from time-series data for fuel consumption. Initial capacity to use the different fuels is set equal to consumption in the initial year. The split between new and old equipment for each fuel is set equal to the split in a model with steady growth. The chosen growth rates equal the observed average growth rates from 1960 to 1970 for each fuel. Table 3 shows the initial capacities of new and old plants. The initial values of the inflexible power plant capacities in table 3 are reduced somewhat to maintain initial total capacity equal to histo-ric demands. Initial fuel shares for flexible capacity equal planned fuel shares.

Simulated and Historical Development of Fuel Demand

Given historical time-series for fuel prices and total demand for fossil fuels from power stations in OECD-Europe, we investigate the model´s ability to explain historical demand for coal, oil, and gas. We estimate fuel premiums, and we examine the importance of short-term flexibility.

First the model is simulated without premiums (P_i =0). Figure 4 shows simulated and historical demands for coal, oil and gas.

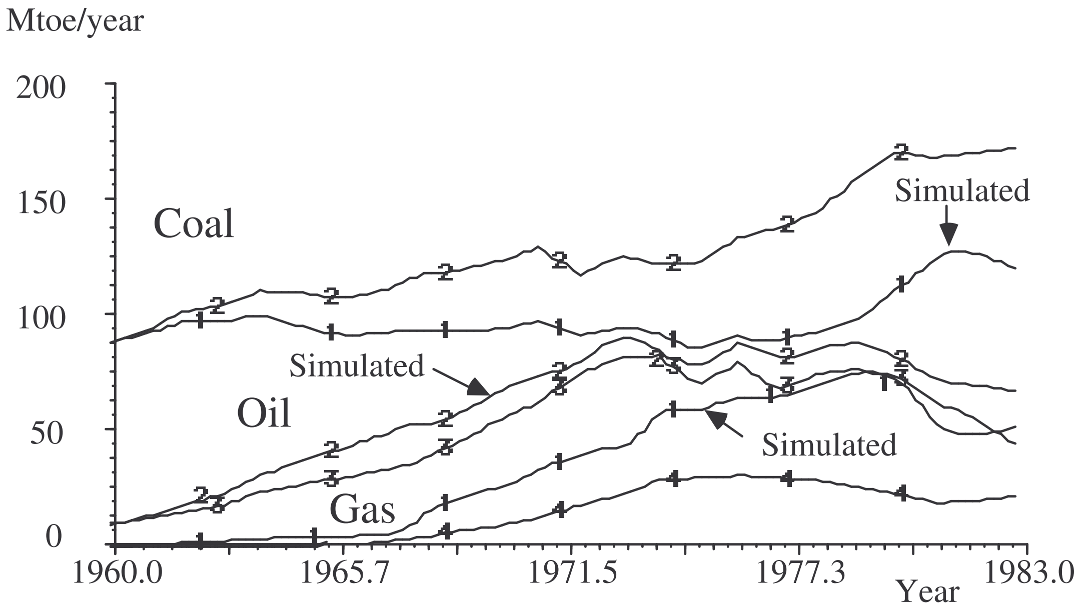

Figure 4: Historical and simulated development of the demand for coal, oil and gas; no premiums and no flexibility. Source for historical data: OECD Energy Balances.

Simulated fuel demand is clearly consistent with the fuel prices shown in figure 3. Oil, which has the lowest fuel, capital and operating costs until 1973, grows quickly during this period. Gas has a prohibitively high fuel price until 1967, and only captures a significant market share when the gas price drops to the oil price level in 1968, and so on.

Simulated behaviour is not well in line with historical development. The short-term dynamics seem correct, while there are growing discrepancies over time. Coal demand is under-estimat-ed, and the model over-estimates the demand for oil and gas. Assuming that the cost data we have used are fairly close to the historical costs, what could have caused the deviation between simulated and real development? The most likely explanation is an active protection of the European coal industry. Indigenous production of coal in OECD-Europe fell from 334 Mtoe/ year in 1960 to 251 Mtoe/year in 1970, and it fell further to 224 Mtoe/year in 1983. Together with productivity improvements in the coal industry, falling production meant continuous reductions in the employment of miners. This provides a motive to protect indigenous coal production. It is also likely that governments possess policy instruments to influence fuel choice. Utilities are either owned by government or they are subject to regulation. The only proof of protection that we have come across is the German "hundertjahrvertrag", which is an overt protection of the domestic coal industry.

The deviation between simulated and actual development indicates that the protection of coal has been considerable. To get an indication of how large the implicit subsidies have been, we calibrate fuel premiums to get a best possible fit between simulated and historical development. Figure 5 shows the simulation results.

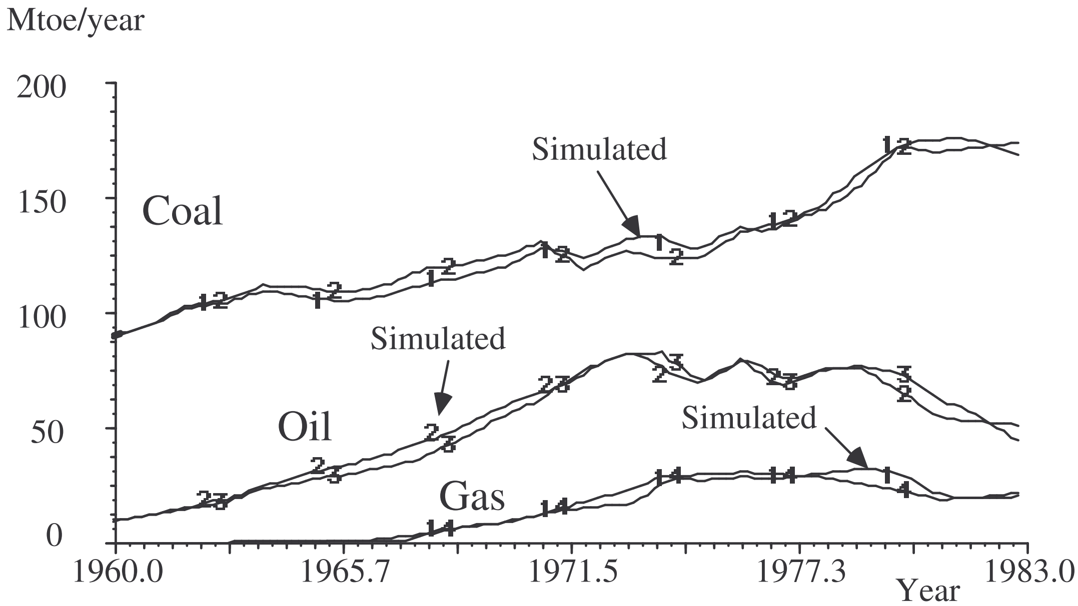

Figure 5: Historical and simulated development of the demand for coal, oil and gas; premiums and flexibility. Source for historical data: OECD Energy Balances.

Judged by figure 5, the model gives a very good explanation of historical fuel substitution. The root mean square errors (RMSE) are 3.9 Mtoe/year for coal, 3.7 for oil and 2.6 for gas. The sum of RMSEs for coal, oil and gas relative to average total energy demand is 5.2 percent. Without premiums the relative RMSE was 35.7 percent.

Table 4: Fuel premiums estimated by calibration of the simulation model to historical data.

	Coal	Oil	Gas 1960-1970-1980
Premiums (USD/toe electricity)	120	0	-100 -60 -60
Corresponding to a percentage 1983 fuel price change of (%):	-29	0	+12
Premiums on flexible capacity (USD/toe electricity)	0	0	-90
Corresponding to a percentage 1983 fuel price change of (%):	0	0	+18

Table 4 shows the estimated premiums. Note that since it is cost differences that determine fuel shares in the multinomial logit model, it is differences between premiums that are meaningful and not the absolute size of the premiums. We have chosen the premium on oil to be 0.

The premium on coal is considerable; it corresponds to a 29 percent price discount on the fuel price of coal in 1983. This is clearly much more than a likely 3 percent over-estimation of the coal price that we mentioned in the data section. The premium on coal reflects effective protec-tion of coal. Since environmental concerns should contribute to a negative premium on coal, protection for employment or import dependence reasons might be even larger than what the above premium indicate.

The negative premium on gas corresponds to a 12 percent increase in the gas price in 1983. Thus, gas is discriminated against more strongly than oil. This premium to oil might reflect oil´s advantages with respect to peak power production. The negative premium on gas in the 1960s is clearly explained by the lack of gas supplies and an adequate distribution system.

Also a negative premium on gas used for flexible capacity helps to improve the fit. The premium is -USD90/(toe electricity), corresponding to a price increase of 18 percent. A small market share for gas makes it less likely to find dual- or multi-firing capacity using gas. It also makes less gas available for power wheeling.

To illustrate the importance of flexible capacity in improving the historical fit, we simulate the model without flexibility, see figure 6. The worsened fit suggests that flexibility is a sound proposition. The sum of RMSEs relative to average total demand deteriorates from 5.2

to 16.4 percent when flexibility is removed. (A recalibration of premiums lead to a minor improvement of the relative RMSE to 16.2 for a gas premium after 1970 of -40 instead of -60 USD/(toe electricity).)

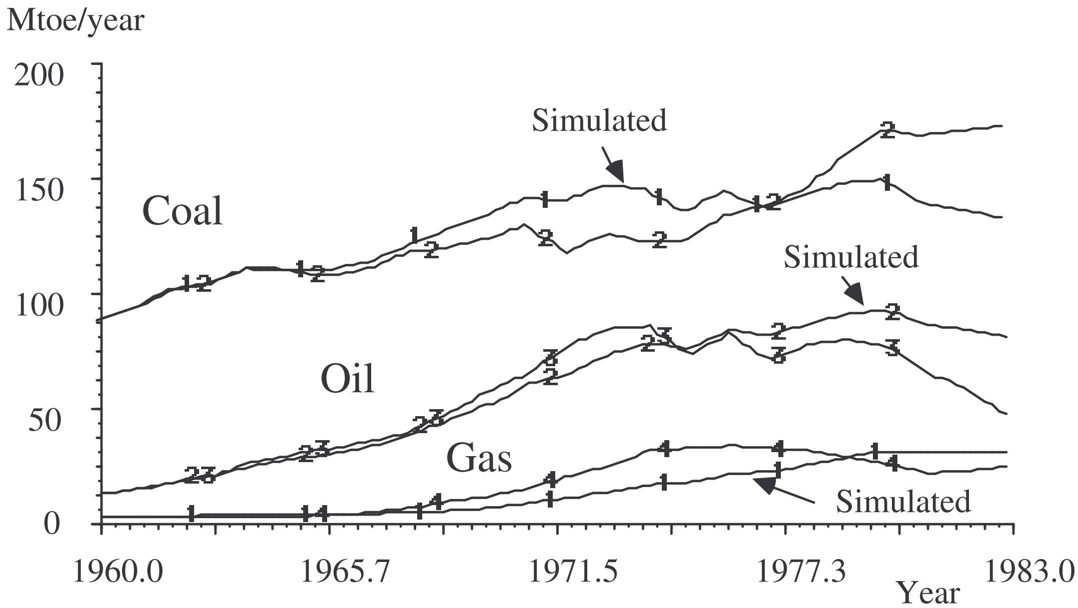

Figure 6: Historical and simulated development of the demand for coal, oil and gas; premiums and no flexibility. Source for historical data: OECD Energy Balances.

To see more clearly what happens with respect to the utilization of the flexible capacity, figure 7 shows the flexible demands. The volumes are in direct correspondence with fuel prices in figure 3. The only distorting factors are minor differences between operating costs and power plant efficiencies for coal and for oil/gas and the imposed negative premium on gas.

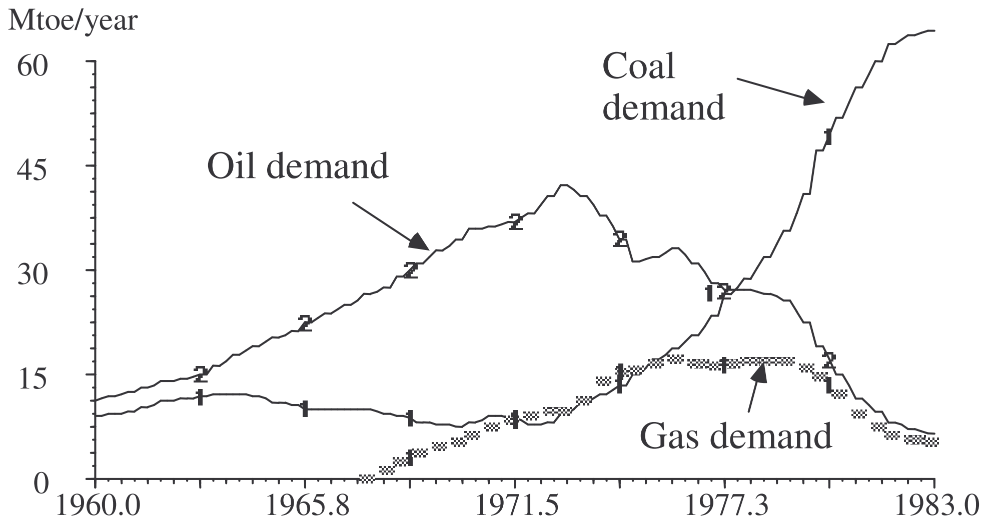

Figure 7: Simulated use of fuels in flexible capacity.

Oil captures nearly all of the flexible part of the market towards the end of the 1960s. After price reductions for gas in the late 1960s, gas becomes just as cheap as oil. However, the negative premium on gas implies a lower market share for gas than for oil. Coal loses the battle with oil in the 1960s and in the early 1970s because of high coal prices. However, after a rapid escalation of oil and gas prices in the late 1970s, coal captures almost the whole flexible market.

Some power stations using coal were actually converted to use oil in the early 1970s. This is probably the explanation why the model over-estimates coal use in the early 1970s, see figure 5. Cost differences of that time, indicate when conversion might take place, and when the underlying assumptions of the model are violated. (Conversion from coal is cheaper than conversion to coal.)

The behaviour of the simulation model is clearly consistent with historical behaviour. Thus the proposed model is not refuted by history. On the other hand, a good fit is not in general a proof that the model is the correct one. Model behaviour is quite insensitive to changes in most of the a priori estimates of the parameters. Typically, calibration of the premiums will bring simulated behaviour quite near the historical development after a parameter change. Therefore, a priori information is important both for the parameters themselves, and for our confidence in the model. A priori data in combination with time-series make a faulty formulation less probable. However, uncertainty in parameters remain, and the model is not likely to be correct for extre-me cost differences.

The results in light of other model studies

The dynamic logit model in other markets

Experience with the dynamic logit model used in other energy markets contribute to our confidence in the model. A number of experiments yield reasonable and consistent results.

Most relevant is a study by Moxnes and Saelensminde(1987) of fuel substitution in power stations in North-America and in the OECD-Pasific region. For North-America the premiums turned out to be almost identical to those found for OECD-Europe. Coal got a positive premium of USD120/(toe electricity), and gas got a negative premium of USD -20/(toe electricity). Like in Europe, the motive for protection of coal is likely to be that it is a domestic fuel providing employment opportunities. In the OECD-Pasific region, the premiums turned out differently. After 1970, coal got an increasingly negative premium of around USD -160/(toe electricity), while gas got an increasingly positive premium, reaching

USD 350/(toe electricity) in 1980. The premiums make sense if the primary concern of the region was to diversify supplies. (Protection of coal should not have high priority since the largest electricity consumer, Japan, produced only about 17 percent of its total coal consumption in 1983).

Studies of industrial fuel substitution in OECD-Europe using the dynamic logit model, Moxnes (1986b) and Moxnes(1986c), gave a zero premium on gas and a small negative premium on coal, USD -10/(useful toe). An attempt was made to exclude fuel demand for other purposes than direct burning. In North-America, Moxnes and Saelensminde(1987) found zero premiums on all fuels. These results for industry make sense if profit maximization dominates national concerns. The latter study find significant premiums of USD -30/(useful toe) on coal and USD 400/(useful toe) on gas in the OECD-Pasific region. One explanation suggested for the latter result is that industrial management in Japan allows for diversification of energy supplies in spite of higher costs.

Finally, the dynamic logit model has been used to explain fuel substitution in households (water and space heating!). The results are summarized in table 5. The ranking is the same in all regions. When two cases are exempted, the largest variation between any two premiums for the same fuel is 36 percent.

Table 5: Fuel premiums for the household sector.

	Coal	Oil	Gas	Electricity
Unit: £/(useful GJ)				
United Kingdom, Moxnes and Vaage (1985)	0.7	0	3.1	3.3
Germany, Moxnes and Vaage (1985)	-1.4	0	0.7	3.0
France, Moxnes and Vaage (1985)	-1.2	0	2.6	3.8
Unit: USD/(useful toe)				
OECD Europe, Moxnes(1986c)	-300	0	180	320
OECD North-America, Moxnes and Saelensminde (1987)	-300	0	220	500
OECD Pasific region, Moxnes and Saelensminde (1987)	-370	0	270	500

Constant elasticity demand models

Constant elasticity demand models of the log-linear type are widely used. They belong to the single equation real demand class of models. Referring to Pindyck(1979), Hall(1986) writes that this class of models "include the use of restrictive functional forms with little or no theo-retical underpinnings; the failure to allow for the relative price influence of all competing fuels *individually*; and not account for such *a priori* restrictions as the sum of individual fuel expen-diture shares being unity." Thus, log-linear demand models should not be expected to yield an appropriate representation of interfuel substitution. However, since the log-linear model is widely used, some of its results might influence the reader´s assessment of the dynamic logit model.

Often single equation models yield surprisingly short adjustment times for energy demand, see for example Prosser(1985), Kouris(1983) and Dahl(1986). This might lead the reader to be suspicious about our assumption of an average adjustment time of about 20 years[6]. To investi-gate this issue we estimate parameters in a log-linear model both from historical time-series and from the output of the dynamic logit model. We use the following model.

$$\frac{D_{i,t}}{E_t} = e^{\beta_i} P_{i,t}^{\beta_{ii}} P_{j,t}^{\beta_{ij}} P_{k,t}^{\beta_{ik}} \left(\frac{D_{i,t-1}}{E_{t-1}} \right)^{\delta_i} \qquad 16$$

$D_{i,t}$ denotes demand for fuel i in year t , and E_t denotes total demand for fossil fuels. The equation explains the market share for each fuel in order to focus on fuel substitution[7]. The market share depends on the fuel prices P_i, the lagged market share, price elasticities β_{ij}, and the lag parameter δ_i. The Cobb-Douglas formulation imply constant elasticities. The lag distribution follows the frequently used Koyck scheme. To estimate the parameters we use Ordinary Least Squares (OLS). OLS is likely to give biased estimates in large samples, while it might give smaller biases than more complicated methods in short samples, Zellner(1984).

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[6]The average adjustment lag equals (6+0.5·15+0.5·30)·0.7+0.5·0.3=20.1 years. The first term represents inflexible capacity with a weight of 0.7. The second term represents flexible capacity with a weight of 0.3 (fraction flexible in 1980). For inflexible capacity there is a 6 year construction time, half of capacity can be changed in 15 years, the other half in 30 years. If capacity were divided into 30 vintages, the average adjustment time would drop to 15.65 years.

[7]Equation 16 is similar to a regular model of energy demand in case total energy demand is not price elastic and in case the income effect on total energy demand is not lagged. The first of these two conditions is usually not met. For power generation, it would be met if electricity prices were set according to average costs, and fuel prices changed such that average costs stayed constant. This has not been the case historically. Thus, using a regular model of fuel demand, the elasticities would reflect demand for electricity in addition to fuel substitution. Also, the lag coefficient would reflect both adjustment delays for electricity demand and fuel substitution.

Results from historical data are shown in table 5, while estimates on data from the dynamic logit model are shown in table 6.

Table 5: Long-term price elasticities and lag coefficients estimated from historical data. * means that the parameter is significant at a 5 percent level. Adjustment time is calculated as -1/log$k$, long-term elasticities as $\beta_{ij}/(1-\delta_{ij})$.

Demand for:	Long-term elasticity with respect to: Gas price	Oil price	Coal price	Lag parameter	R^2	Adjustment-time:
Gas	-1.32	-2.95	+7.29 *	0.891 *	98.1	8.7
Oil	-0.18	-1.24 *	+1.22	0.852 *	97.4	6.2
Coal	+0.36	+0.68 *	-0.99 *	0.881 *	98.2	7.9

Only half of the long-term price elasticities from historical data are significant at the 5 percent level; two of the non-significant elasticities have opposite signs of what should be expect. The adjustment times vary between 6.2 and 8.7 years. Thus the estimated adjustment times are on average 2.6 times shorter than the average adjustment time in the simulation model.

Table 6: Long-term price elasticities and lag coefficient estimated from simulated data. * means that the parameter is significant at a 5 percent level. Adjustment time is calculated as 1/(1-k),long-term elasticities as $\beta_{ij}/(1-\delta_{ij})$.

Demand for:	Long-term elasticity with respect to: Gas price	Oil price	Coal price	Lag parameter	R^2	Adjustment-time:
Gas	-2.0 *	+1.3 *	+0.7	0.68 *	99.3	2.6
Oil	+0.1	-1.1 *	+1.2 *	0.80 *	98.6	4.5
Coal	+0.2	+0.6 *	-0.8 *	0.87 *	98.4	7.2

Table 6 shows that the estimates from the synthetic time-series are of approximately the same quality as the estimates from actual data. R-squares are a little higher, as should be expected since the synthetic data contain no randomness. Like for historical data, adjustment times are under-estimated. The average adjustment time is 4.2 times shorter than in the simulation model. Thus, this experiment does not invalidate the dynamic logit model. Rather, it seems to be the econometric estimates, using the Koyck model, that are biased. This is not surprising since a large number of combinations of adjustment lags and price elasticities often fit data, EMF (1980). Moxnes(1986a) gives examples where this property leads to biased estimates.

The results also support the finding from the logit model, that elasticities increase with decreas-ing market shares. All significant elasticities fall into this pattern. While implicit elasticities vary with market share in the logit model, the log-linear model has constant elasticities. Thus, if market shares change after the estimation period, the log-linear model is not likely to give a correct description of the market.

Translog cost models

Knowing an energy consumer´s production function, interfuel substitution can be deducted under the assumption that total costs are to be minimized. By making use of the dual relation-ship between the cost and the production function (Shepard, 1953), Christensen, Jorgenson and Lau(1973) suggested to represent the production frontier by translog cost functions (quadratic in logarithms of inputs). This approach allows for a rather flexible description of production functions and substitution. Certain restrictions are usually applied a priori or to test hypotheses. Pindyck(1979) have shown that the translog cost function implies elasticities to be functions of market shares, like we have shown for the logit model. From Shepard´s Lemma the derived expenditure share equations are found by differentiating the cost function with respect to the prices. Equation 17 shows a dynamic model of expenditure shares S_i used by Hall(1986).

$$e^{S_{i,t}} = e^{\beta_i} P_{i,t}^{\beta_{ii}} P_{j,t}^{\beta_{ij}} P_{k,t}^{\beta_{ik}} E_t^{\beta_{iE}} e^{\gamma t} e^{\delta_i S_{i,t-1}} \qquad 17$$

Comparing to equation 16, we see that Hall includes the additional explanatory variables total energy demand E and a time trend t. The important difference between the two equations is that volume shares in equation 16 are replaced by the exponent of the expenditure shares in equation 17. This means that β_{ij} should not be interpreted as a price elasticity. Rather implicit price elasticities depend on the β´s and the expenditure shares, as shown by Pindyck(1979). Equation 17, together with the restriction that $\Sigma S_i=1$, is the model that should be used for forecasts or policy studies, not the implicit price elasticities. On this background, it is surpris-ing how much attention price elasticities get when fuel substitution is studied by translog cost functions. If worst case, changing market shares (and prices) could make elasticity estimates obsolete while a study is waiting to be published.

Two problems with the translog approach seem to make it less appropriate to describe fuel substitution than the dynamic logit model. Our discussion is restricted to processes where the potential for substitution is known a priori, and the logit model can be used with no or minor modifications. Firstly, the translog model is complex, and the coefficients do not have simple real-life interpretations. This makes it difficult for a decision maker to build confidence in the model, and for the analyst to apply Bayesian estimation techniques. If a translog model had been estimated over a period with limited availability of gas, it would probably be difficult to compensate for this when the model is used for predictions in a period with improved avail-ability.

Secondly, results obtained by the translog method are not convincing and thus useful from a practical point of view. Not because the statistical measures are worse than for other methods. On the contrary, several well founded a priori restrictions conserve degrees of freedom, such that the results might be better than those obtained with single equation demand models[8]. The problem is rather that the historical time-series do not contain enough information. The coef-ficients are sample dependent in a complicated manner. For example, in a study of the residen-tial sector, Rushdi(1986) found that oil and gas were not substitutes, but nearly significant complements. Rushdi was not able to explain this unlikely result. There seems to be no a priori support for the finding. On the contrary, there are lots of reasons to expect oil and gas to be substitutes. With one such suspicious result in mind, is it likely that a decision maker will have confidence in the other parameters? Remember that the reasonable coefficients are estimated in concert with the erroneous ones.

Hall(1986) concludes from a study of the industrial sector that "it has been shown - that - nor the preferred non-homothetic equality model can provide a full set of satisfactory own-price and cross-price elasticities of demand - those elasticities which are significant can vary substan-tially in magnitude across alternative model specifications". Pindyck(1979) also found many elasticities to be insignificant, while he found correct signs on impressive 89 of 90 elasticities concerning coal, gas, and oil. One likely reason for this was that he used pooled time-series data for a cross-section of ten countries. Another reason was probably that he avoided data after the oil price jump of 1973. The dramatic price increase was followed by slow volume adjustments, which called for a dynamic model rather than his static one.

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[8]Hall(1986) conclude from a study with a translog cost function that "it is the case that the less restricted the model, the fewer correctly signed statistically significant own-price and cross-price elasticities can be obtained".

Conclusions

We have used a dynamic model to study substitution between coal, gas, and oil in OECD-European power generation. Total demand for electricity as well as fuel prices have been considered exogenous.

Inflexible generating capacity has been modeled by a putty-clay formulation. Investments have been split on the different fuels according to a multinomial logit model. Vintages have been constructed for plants under construction, new and old operating capacity. Short-term switch-ing between fuels in flexible capacity has also been determined by a multinomial logit function. The model has been constructed such that all parameters have a real life counterpart. This fea-ture allowed the use of a priori data for all parameters. In line with Bayesian theory, only the most uncertain parameters pertaining to preferences have been adjusted to improve the histo-rical fit. The relative root mean square error for the deviation between historical and simulated behaviour bacame 5.2 percent. When disregarding short-term flexibility, the fit deteriorated to 16.2 percent.

Comparing the dynamic logit model to constant elasticity models or translog models, it is the focus on a priori data that makes the model unique. Like translog models, our model predicts that elasticities vary with fuel shares. Estimation of a constant elasticity model showed this effect for our data set. The dynamic logit model had an average adjustment time of about 20 years, which is 2.6 times longer than the adjustment times that came out of the constant elasticity model. By estimating the latter model on data from the dynamic logit model, even shorter adjustment times resulted. Thus, it seems that the constant elasticity model under-estimates adjustment times, while the dynamic logit model might well be correct.

A survey of studies made by the dynamic logit model showed that it consistently produces reasonable results over a period with two dramatic price increases. A survey of a few studies made by translog models, indicated that elasticities frequently come out with wrong signs. When they come out with correct signs, they are often insignificant, although there are strong a priori reasons to believe that the elasticities are different from zero.

Although the chosen data set from electricity production did not call for model revisions, the dynamic logit model will not pass all kinds of extreme tests[9]. Firstly, when a fuel option is not available, like gas in the 1960s in our case, we have to rely on a fitted negative premium on gas to get the correct fuel shares. This fitted premium is not directly observable. To make proper use of a priori information in this case, investments in the fuel with limited

[9]On extreme testing see Bell and Senge(1980), Senge(1980), and Zellner(1981).

availability would have to be limited volumewise. This short-coming applies to flexible capacity as well.

Secondly, if the value of a fuel option changes as a function of its market share (in a different fashion than the other fuels), this effect should be explicitly modeled. An example might be the advantages of light fuel oil for peak power purposes. Thirdly, great price or cost differences are likely to precipitate rebuilding of existing "inflexible" power plants. An example is the retrofitting of a few coal fired plants to burn oil in the early 1970s. Rebuilding or premature re-placement could be included in the model, at the cost of a considerable increase in complexity.

Finally, what useful results came out of the study? The most striking finding was that there is a bias towards choosing coal. The estimated premium on coal corresponds to a rebate on the 1983 coal price of 29 percent. A likely explanation is that coal is preferred for employment reasons and perhaps to reduce import dependence. Gas got a minor negative premium compared to oil. A previous study found nearly identical results for North-America.

Keeping the caveats in mind, the model should be well suited for policy studies and forecasting. The model can be used to quantify taxes to reduce oil dependence or CO_2 emissions. It can be used to calculate net-back prices, which take account of costs, efficiencies and estimated premiums. For forecasting purposes, it can be used to calculate the consequences of changes in costs, efficiencies, premiums, flexibility, lifetimes etc. Finally, because of its focus on real-life interpretation, the model should be useful for teaching purposes.

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