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ECONOMIES OF SCALE AND TECHNOLOGICAL CHANGE IN ELECTRICITY GENERATION IN THE NETHERLANDS**

BY

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1 INTRODUCTION

A well-known problem in economic theory is the distinction between economies of scale and technical progress. A wide body of literature on this topic exists and a lot of applied research has been done. An important field of such applied research is the American electricity generating industry. Apart from the importance of this industry *per se*, the reasons for this particular application are the abundant availability of data on the one hand, and the obvious existence of both economies of scale and technological change on the other. Although the applied research is generally directed to the overall effects of economies of scale and technological change in electricity generation, our data only allow us to study the effects on fuel efficiency, *i.e.* the energy content of the electricity generated expressed as a ratio of the energy content of the fuel input used.

The aim of this article is to investigate the effects of economies of scale and technological change on the fuel efficiency of steam-electric turbines in The Netherlands. We also wish to compare our conclusions with those found in the, mostly American, literature. As far as we know, an analysis of economies of scale and technological change in the Dutch electricity industry has never been carried out before, not even with a limited set of data as we have at our disposal. From this analysis some indications may be derived about the planning of steam electric turbines, especially about their optimal size.

In our opinion the analysis gives some interesting insights with respect to electricity generation in The Netherlands between 1960 and 1980. As will

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be shown below, significant scale effects are present for turbines below 200 MW, whereas fuel efficiency does not vary much between turbines of 200 up to 650 MW. Moreover, technological improvements in thermal power generation only occur before 1967, while after that year no significant effects on fuel efficiency can be observed. There are no interaction effects between the size and vintage of the machines. This means that the effect of size on fuel efficiency does not vary with the vintage. Analogously, vintage effects are independent of size. Furthermore, the fuel-type of steam electric turbines (coal, oil, gas or mixed) has turned out to be invariant with respect to fuel efficiency.

In the second section a brief summary of the literature on economies of scale and technological change in thermal power generation will be given. In most of the studies reviewed the effects of technological change and economies of scale are investigated for total costs or for different cost categories. However, our data only permit to study these effects with regard to fuel efficiency. This will be elaborated upon in the third section. Finally, in the fourth section some concluding remarks will be made.

2 SURVEY OF THE LITERATURE

The literature surveyed concerns economic studies of the production structure of boiler-turbine-generation (BTG) of electricity. The aim of these studies is generally restricted to an investigation of scale and vintage effects. Since an excellent review of the literature up to 1964 has been given by Galatin,[1] our survey will mainly cover some relevant studies that have appeared since 1964, including Galatin's.

In section 2.1 we will deal with the way in which the production structure of the BTG industry can be represented. This will provide some background for a clear understanding of the empirical findings on economies of scale and technological change. A review of those findings will be presented in section 2.2.

2.1 *The Representation of the Production Structure*

The factors of production

In all studies at least two factors of production are distinguished: capital and fuel. Capital is given once the production unit has been installed, while fuel

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[1] Galatin (1968).

input varies with output. According to Galatin: "Each machine, when in place, uses inputs of variable factors, fuel, labour and water, to produce electricity. It will be shown . . . that labour is virtually a fixed factor. Fuel cost dominates variable cost and in this study fuel is considered as the only variable input in terms of the *ex post* production function."[2] In the long run, however, capital can be regarded as a variable production factor.

In most cases capital is measured by a money value[3] and sometimes in physical terms, by means of plant capacity.[4] However, complementary to this measure – or when capital is not measured explicitly – capital is represented by the attributes of a plant or a turbine. These attributes are size (in MW), vintage and, frequently, fuel-type.[5] According to several authors these attributes can only characterize a turbine, not a plant, for reasons of technological homogeneity. When only data on plants are available, then solely plants consisting of identical turbines are regarded in the empirical investigation.[6]

Fuel is considered as a homogenous input which can be measured in physical terms, e.g. *BTU* or *GJ*.[7] However, in some studies fuel input is disaggregated into several categories (e.g. coal, oil, gas) and explicit allowance is made for interfuel substitution. The reason for the choice of this conception is that electric utilities often have alternative fuel burning equipment and can then respond to relative price differences between these different fuels.[8]

Sometimes a third factor of production is distinguished: labour. In all studies which take into account this production factor, labour is assumed to be complementary to capital once the production unit has been installed.[9]

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[2] Galatin (1968, p. 33). See also Wills (1977, p. 498); Cowing (1974, p. 137).

[3] See, for example, Komiya (1962, p. 158); Galatin (1968, p. 129); Joskow and Mishkin (1977, p. 721).

[4] Atkinson and Halvorsen (1976, p. 976). A partly comparable definition of capital has been used by Dhrymes and Kurz (1964, p. 298): capital input equals plant capacity multiplied by the fraction of time during which the machine was actively engaged in generation.

[5] Some studies on electricity production use observations on the firm level instead of on the plant or turbine level; see Christensen and Greene (1976); Huettner and Landon (1978). In these cases capital can not be represented by attributes because of a lack of technological homogenety. Apart from size, vintage and fuel type, turbines can be characterised by their planned utilisation rate and fuel efficiency; see Stewart (1979, pp. 551, 564).

[6] Galatin (1968, p. 97); Wills (1977, p. 498); Cowing (1974, p. 148).

[7] See for example, Galatin (1968, p. 42); Cowing (1974, p. 137).

[8] Atkinson and Halvorsen (1976); Griffin (1977); Joskow and Mishkin (1977).

[9] See, for example, Galatin (1968, p. 33); Wills (1977, p. 498); Cowing (1974, p. 137); Atkinson and Halvorsen (1976, p. 961).

Labour is either measured physically (man-hours) or in money value (wage-costs).

The production function: ex ante versus ex post

In production studies usually a distinction is made between *ex ante* and *ex post* situations. In the *ex ante* situation the entrepreneur can choose between different production units, each characterized by a particular combination of capital, labour and fuel. In terms of a vintage model, the *ex ante* situation is *putty*; in a *clay ex ante* situation each unit would be characterized by the same input combination. In the *ex post* situation certain production units have been chosen and installed. Here one can also distinguish between a putty situation – substitution *ex post* is possible – and a clay situation – the input coefficients are fixed *ex post.* In the studies reviewed the assumption of a putty-clay structure seems to be dominant, although a putty-putty or a clay-clay production structure has been assumed by some authors.[10]

As we have mentioned above, the aim of all studies is to investigate the properties of the *ex ante* production structure, *i.e.* economies of scale and technological change, using data on the *ex post* production structure. This is possible since a turbine represents, at full capacity operation just after it has been installed, a point on the *ex ante* function, as it exists at the moment of the vintage of the turbine. However, it should be noted that it is necessary to make assumptions about the *ex post* production function in order to infer from data on actual production, full capacity points from which relevant characteristics of the *ex ante* function can be observed.

In this subsection we wish to deal with three subjects that are relevant with respect to the production structure of the BTG industry and in which the above mentioned distinction between *ex ante* and *ex post* will be elaborated. First, different assumptions concerning the *ex post* production structure will be mentioned. Second, some remarks will be made about the form of the *ex ante* production function. And finally, the question will be raised of how to infer from *ex post* data characteristics of the *ex ante* production function, e.g. economies of scale and technological change.

A convenient assumption about *the ex post* production function is that input coefficients are fixed *ex post,* since the chosen point on the *ex ante* function can then be directly observed from the actual situation. Some authors use in this case only observations on machines concerning the first year after installation, which is supposed to be an acceptable approximation

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[10] See respectively Wills (1977, p. 498 (putty-clay)), Galatin (1968, chapter 5 (putty-putty)) and Komiya (1962 (clay-clay)).

of full capacity operation.[11]

Galatin, on the other hand, assumes that the fuel input coefficient varies with the degree of capacity utilization: the higher the utilization, the lower the input coefficient.[12] The differences in the *ex ante* situation are then reflected in different parameters of the fuel input equation *ex post*.

Finally, one can explicitly allow for interfuel substitution *ex post*. Then an *ex post* production function is assumed in which capital and labour are fixed and different fuels are variable inputs.[13] Here also the differences in the situation *ex ante* are reflected in the differences in the parameters of the *ex post* production function.

In several studies a specific form of the *ex ante* production function has been assumed, whereas in other studies only a specific form of the cost function has been assumed.[14] The production function has been specified in various ways: fixed coefficient,[15] Cobb-Douglas,[16] CES[17] and translog.[18] The latter form implies no *a priori* restrictions on the possibilities of subsitution, such as a constant elasticity of substitution.

Generally, no explicit arguments are given to defend the choice of the functional specification of the *ex ante* production function, except that it turns out to fit well to the data or that it allows for a variety of assumptions with respect to the possibilities of substitution.[19] Some authors, however, refer explicitly to the technology of electricity generation in discussing the form of the *ex ante* function.[20] Others leave room for interfuel substitution in the specification of the *ex ante* function.[21]

A rather crude way of investigating the *ex ante* production structure using *ex post* data is to distinguish clusters of turbines of approximately the same

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[11] See, for example, Komiya (1962, p. 157); Dhrymes and Kurz (1964, p. 297). It should be noticed that Komiya adjusted his data to full-capacity working of the production units.

[12] Galatin (1968, pp. 34–37).

[13] Atkinson and Halvorsen (1976).

[14] With respect to our empirical investigation in section 3 it is not relevant to deal explicitly with the choice between estimating a production function or a cost function. See Christensen and Greene (1976, pp. 658–659).

[15] Komiya (1962, p. 158).

[16] Nerlove (1960 (cited by Galatin 1968, pp. 74–84)).

[17] Dhrymes and Kurz (1964, pp. 288–289).

[18] Atkinson and Halvorsen (1976, pp. 961–966); Christensen and Greene (1976, pp. 659–662); Griffin (1977, pp. 756–760).

[19] See the references in note 18.

[20] Cowing (1974, p. 148).

[21] Atkinson and Halvorsen (1976); Griffin (1977); Joskow and Mishkin (1977).

size and vintage (possibly also the same fuel-type). The characteristics of each cluster are given by the parameters of the *ex post* production function. Then the differences between clusters of the same size but different vintages are attributed to technical progress, whereas differences between clusters of the same vintage but different sizes are attributed to economies of scale.[22] A more elaborated way of investigating scale effects and technological change is to define an *ex ante* production function in which vintage and size appear as explanatory variables.[23]

2.2 *Empirical Results on Economies of Scale and Technological Change*

Economies of scale

Traditionally economies of scale have been a main characteristic of thermal power generation. Relatively substantial economies-of-scale effects with respect to all three production factors have been found by authors who use data on plants built between 1930 and 1960.[24] However, when data on more recently built units are used, it turns out that capital and fuel-augmenting scale effects become less important. This is due to the fact that units of later vintages are, generally speaking, larger units. According to Wills: "The elasticity of efficiency [*i.e.* fuel efficiency – v. H., M.] with respect to unit size varies over the observed range of unit sizes. It is considerable for units below 100 megawatts but (falls too close) to zero for plants above 250 megawatts."[25] A somewhat different interpretation of the relationship between scale economies and technological change has been given by Cowing: ". . . the basic manifestation of technical change has occurred in the form of extensions of the long-run average cost curve to lower cost and larger sized units rather than in a general lowering of the curve for all sizes. The result has been a scale-augmenting technical change . . ."[26]

Turning from the unit-level to the firm-level, significant scale effects are present at moderate firm sizes, but at larger firm sizes the average cost curve becomes flat or is even increasing, implying diseconomies of scale.[27]

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[22] Komiya (1962, pp. 160–165); Galatin (1968, pp. 107–117); Dhrymes and Kurz (1964, p. 305); Christensen and Green (1976, pp. 668–673).

[23] Cowing (1974, p. 149); Wills (1977, pp. 503–509).

[24] Komiya (1962, pp. 161–165); Dhrymes and Kurz (1964, pp. 303–312); Galatin (1968, pp. 120–126, 134, 137); Cowing (1974, pp. 148–150).

[25] Wills (1977, p. 508). See also Atkinson and Halvorsen (1976, p. 972); Joskow and Mishkin (1977, pp. 723, 724).

[26] Cowing (1974, p. 150). However this conclusion is based on observations of plants built between 1947 and 1965.

[27] Respectively Christensen and Green (1976, pp. 667–673), Huettner and Landon (1978, pp. 903–908).

Technological change

Most studies dealing with electricity production endeavour to give indications about the effects of technological change. Especially the phenomenon of embodied technological change has been evaluated. According to Cowing, who explicitly allows for vintage effects in the *ex ante* function, the yearly rate of capital-augmenting technological change is found to be 9 to 10 percent, while the rate of fuel-augmenting technological change is about 2 percent.[28] Authors who try to evaluate technological change by comparing different vintage groups are inclined to conclude technological change to be less important than economies of scale, although the latter holds especially for small-sized units, as has been mentioned above.[29]

Substitution effects

As noted in section 2.1 generally three factors of production can be distinguished with respect to thermal power generation: fuel, labour and capital. In a relatively large number of studies, however, a model has been used which does not allow for *ex ante* factor substitution.[30] An important exception is the study which has been carried out by Dhrymes and Kurz. These authors allow for substitution between capital and fuel, where the elasticity of substitution has been found to fall with the size of the plants, whereas technological change is invariant with respect to this substitution effect.[31]

In those studies, which make explicit allowance for interfuel substitution, the *ex post* substitution effects between coal, oil and gas input are found to be substantial.[32]

The effect of the fuel type

In those studies, where a distinction has been made between groups of production units according to their fuel type, coal-burning units seem to be significantly more efficient than oil- or gas-burning units. In contrast, coal-burning units use relatively more capital than noncoal-burning units.[33]

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[28] Cowing (1974, p. 149). These results may reflect the small changes in energy prices before 1973.

[29] Komiya (1962, pp. 161–165); Dhrymes and Kurz (1964, pp. 303–312).

[30] Komiya (1962); Galatin (1968); Wills (1977).

[31] Dhrymes and Kurz (1964, pp. 303–312). Cowing also allows for *ex ante* factor substitution, but he concludes that the relative price of fuel to capital does not bring about significant substitution effects between those two factors; see Cowing (1974, p. 149).

[32] Atkinson and Halvorsen (1976, pp. 972–973); Griffin (1977, p. 769).

[33] Wills (1977, p. 508); see also Komiya (1962, pp. 161–165).

Furthermore, it has been found that technological change is stronger for coal and mixed units than for noncoal units.[34]

3 RESULTS OF THE EMPIRICAL INVESTIGATION

3.1 *The Data Used*

In this section we wish to analyse the effects of economies of scale and technological change on the fuel efficiency of boiler-turbine-generation of electricity in The Netherlands. With the data available we can only study the effects on fuel efficiency and not those on capital costs, labour costs or total costs. The scarce data also means that no conclusions can be drawn about possible substitution effects between the production factors. Neither is it possible to analyse interfuel substitution, because data on the actual usage of fuels (coal, oil or gas) are not on hand.

The data are presented in Van Helden and Muysken (1980); for the largest part they have been collected from answers to questionnaires to the electricity companies. These data concern 89 turbines, covering a considerable portion of electricity production in The Netherlands (for example 76% of total electricity generation and even 93% of total boiler-turbine-generation of electricity is covered by the available data in 1973). For each turbine data are available on vintage and capacity; and for each year of operation on hours worked, output, fuel input (both measured in KJ) and fuel-type. Data on hours worked will be left out of consideration until later, in the final section and Appendix C, where some indications will be given about the availability (and utilisation) of turbines, related to their size and vintage.

As has been shown in section 2.1, economies of scale and technological change can be analysed by considering the effects of capacity and vintage of a turbine on its fuel efficiency, occasionally differentiated with respect to the fuel-type. Hence, each turbine should be characterised by capacity, vintage, fuel-type and fuel efficiency. The first two characteristics can be derived in a straightforward manner from the data. However, both fuel-type and fuel efficiency can differ from year to year, because of differences in the yearly operation of a turbine.

With respect to fuel-types the type which coincides with the year of maximum fuel efficiency of the turbine has been chosen (see below). In most cases this type was also dominant over the operational period of the turbine. It has turned out that only the types 1 (coal), 2 (heavy oil), 3 (coal/oil), 6 (light oil/

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[34] Galatin (1968, pp. 121–126).

gas) and 7 (gas) occurred. Other possible fuel types – 4 (light oil), 5 (propane gas) and 8 (coal/gas) – were not present in the available data.

With respect to the fuel efficiency of a turbine one might take the *efficiency in the first year of operation*, which represents the technical possibilities of the machine.[35] This procedure has two drawbacks: those turbines of which the vintage lies outside the observation period should be neglected and the first year of operation may, for whatever reason, have been a relatively inefficient year. Alternatively, one might choose for the *maximal efficiency* of the turbine during its lifetime. A drawback of this alternative is that this maximal efficiency may have been achieved under expceptional circumstances. Therefore a correction of the maximal efficiency of some turbines should be taken into consideration.[36] A third possibility is to take the *average efficiency* over the lifetime of a turbine. This alternative does not have the drawbacks of the aforementioned alternatives, but it represents the technological possibilities in a remote way. All three possibilities are presented in

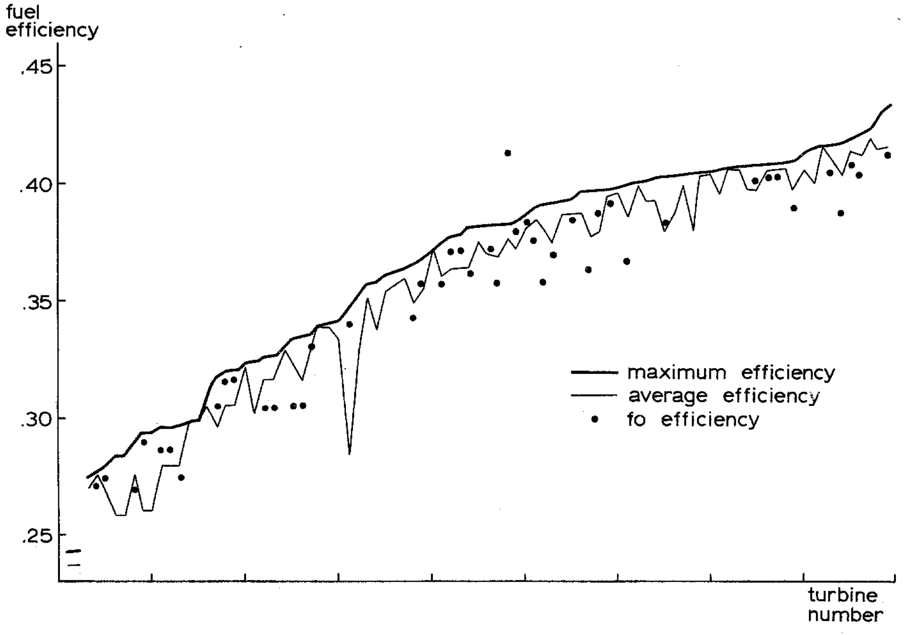

Figure 1 – Maximum fuel efficiency (in the order of their magnitude) with the corresponding average and *fo*-efficiency.

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[35] Komiya (1962, p. 157); Dhrymes and Kurz (1964, p. 297).

[36] In Appendix A the relevant corrections of maximal fuel efficiency are mentioned and explained.

Figure 1. In the figure the maximal efficiencies are depicted in the order of their magnitude, together with the corresponding average and first-year-of-operation (*fo*) efficiency. These three efficiencies are given on the vertical axis, whereas the identification number of each turbine is given on the horizontal axis. The identification numbers are arranged in such a way that the turbines are in an increasing order of maximal efficiency.

The *fo*-efficencies are represented by a dot because for several turbines no data are available for the first year of operation. From the figure one sees that in many cases both the average and the *fo*-efficiency lies below the maximal efficiency. Moreover, it frequently occurs that the *fo*-efficiency can hardly be said to represent the technological possibilities of a turbine. For that reason we shall further represent the efficiency of a turbine by its maximal efficiency.[37]

3.2 *Empirical Results on Economies of Scale and Technological Change*

Classification of the data

A stratification of the data is given in Table 1. An important characteristic of the data is that 40 of the 89 turbines, only covering 17 percent of total capacity, were built before 1962 and/or have a capacity below 100 MW. The table indicates that vintage, capacity and fuel-type are not independent. Turbines of a younger vintage usually have a larger capacity: for the vintage periods < 56, 56–62, 63–67, 68–75 and > 75 the average capacity of a turbine is 47, 85, 132, 272 and 605 MW, respectively. Moreover, turbines of a younger vintage usually are characterised by the fuel-type gas/oil or gas (types 6 and 7), whereas older turbines are of the coal, oil or coal/oil type (types 1, 2 and 3).

Looking at the average (maximal) fuel efficiency in each vintage/capacity cell of Table 1 reveals increasing returns to scale for the vintage groups up to 1968 (until 450 MW) and for the vintage group between 1968 and 1976 (until 200 MW). With respect to the vintage effects a more diverse pattern emerges: for the capacities between 50 and 150 MW the vintages between 1962 and 1968 are less efficient than those for vintages between 1956–1962 and 1968–1975, whereas for the capacities between 150 and 300 MW the vintages between 1968 and 1976 are less efficient than those for vintages between 1962 and 1968.[37a] There appears to be no significant influence

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[37] See note 36.

[37a] One should realise that turbines of the same size may play a different role in overall electricity production depending on the year of installation. For example, a 100 MW tur-

TABLE 1 – THE MAXIMUM FUEL EFFICIENCY FOR DIFFERENT VINTAGE/CAPACITY GROUPS*

Vintage/ Capacity (MW)	< 56		56–61		62–67		68–75		> 75	
0	0.272(8)		0.324(3)							
50	0.269(7)	0.290(1)	0.318(1)	0.327(2)						
51	0.334(15)		0.366(8)		0.360(4)		0.382(2)			
100	0.335(13)	0.327(2)	0.370(6)	0.353(2)	0.369(2)	0.349(2)		0.382(2)	–	
101	–		0.377(4)		0.375(11)		0.402(4)			
150			0.389(2)	0.364(2)	0.392(2)	0.371(9)		0.402(4)	–	
151	–		0.396(1)		0.407(5)		0.405(5)			
200			0.396(1)		0.391 (1)	0.410(4)		0.405(5)	–	
201	–		–		0.414(2)		0.404(2)			
300					0.410(1)	0.418(1)		0.404(2)	–	
301	–		–		–		0.412(7)		–	
450								0.412(7)		
>450	–		–		–		0.407(4)	0.407(4)	0.410(4)	0.410(4)

* In each capacity/vintage cell the average maximum fuel efficiency is represented and between brackets the number of turbines for which this average has been computed. Moreover on the left hand the average maximum fuel efficiency for the coal and or oil type is represented and on the right hand for the oil and or gas type (with the number of turbines between brackets).

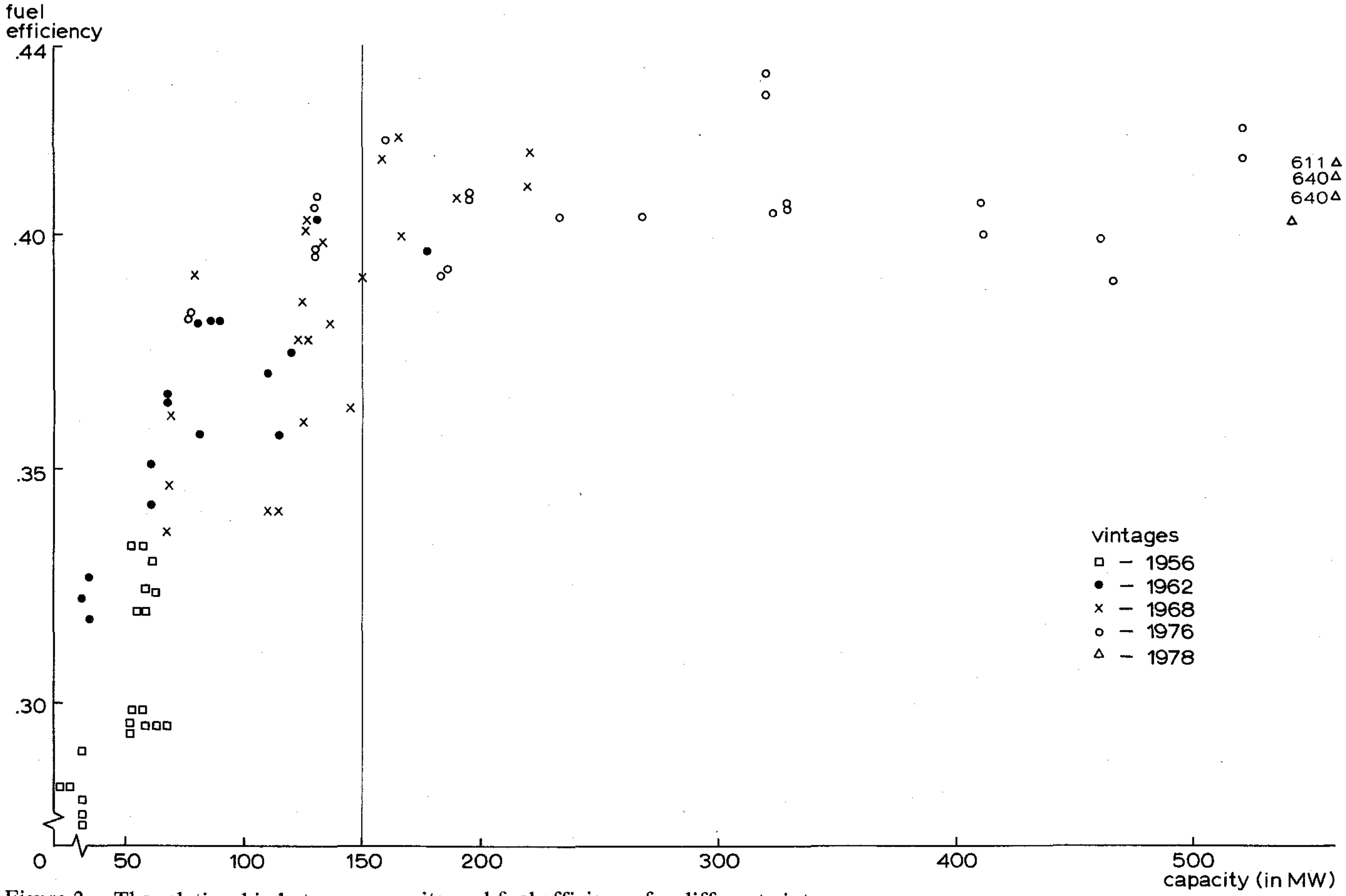

Figure 2 – The relationship between capacity and fuel efficiency for different vintage groups.

between the fuel-types coal and/or oil on the one hand and the fuel types oil and/or gas on the other hand (see in each cell of Table 1 the fuel efficiencies on the left- and right-hand side respectively). However, one should realize that in none of the vintage/capacity cells can more than two turbines of one type category be compared with more than two turbines of the other type category, which makes a comparison rather haphazard.

Given the interdependence between vintage and capacity, it may be difficult to distinguish between scale and technological change effects concerning the fuel efficiency of turbines. However, some indications can be found in Figure 2, in which each turbine is plotted with respect to its capacity and its efficiency; moreover the different vintage periods are indicated in the figure. From the figure it is evident that there are strong scale effects until 150 or even 200 MW; for higher levels of capacity no scale effects can be observed. With respect to the vintage effects, the vintages before 1956 are evidently less efficient than those between 1956 and 1962. The vintages between 1962 and 1968 appear to be still somewhat more efficient than those between 1956 and 1962. However, the post-1968 vintages can hardly be said to be even more efficient. Hence, one might expect (decreasing) vintage effects until 1968 and strong scale effects to the capacity level around 200 MW. We want to investigate these effects in a more thorough way.

Analysis of variance

A first possibility to analyse the effects of scale and technical change on fuel efficiency in a more sophisticated way is by means of analysis of variance (see also note 22).[38] In analysis of variance a distinction is made between one dependent variable (fuel efficiency) and one or more independent variables (size, vintage and – although expectations about effects on the dependent variable seem to be doubtful – fuel-type). Analysis of variance has been chosen primarily because of its ability to show interaction effects of two or more independent variables.[39] Furthermore, independent variables are

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bine installed in 1960 may be used as a base load unit (more than 6000 worked hours per year) whereas a turbine of the same size installed in 1975 may be used as a middle load unit (worked hours per year between 3000 and 6000).

38 Computations are made by means of the Statistical Program for the Social Sciences (SPSS); the terminology with regard to analysis of variance is taken from the SPSS manual; see Kim and Kohout (1970).

39 An interaction effect between the independent variables A and B implies that the effect of a change in variable A on the value of the dependent variable varies with the value of variable B. So, an interaction effect should be distinguished from the occurrence of multicolliniarity between independent variables.

allowed to have a nonmetric scale which evidently holds for the variable fuel-type. Although the two other independent variables, size and vintage, are metric variables, they will be treated as categorial variables and so become nonmetric.[40]

From the analysis of variance two conclusions can be derived. First, the effects of size and vintage on fuel efficiency are statistically significant, while those for fuel-type are not; the F-values for size and vintage are significant at the 1 percent level. In the second place there are no statistically significant interaction effects of vintage and size on fuel efficiency.[41]

In addition to analysis of variance, a multiple classification analysis can be used in order to show the pattern of the relationship between the statistically significant independent variables and the dependent variables; see Table 2.

In the second column of Table 2 the mean value of fuel efficiency for each size or vintage category, expressed as a deviation from the grand mean (= 0.36), has been given. In calculating these values, the effect of size on fuel efficiency has not been adjusted for the vintage effect; neither has the effect of vintage on fuel efficiency been adjusted for the size effect. The numbers in the third column of Table 2 are the adjusted mean values for each size or vintage category, again expressed as deviations from the grand mean. Note that the effect of each variable diminishes when it is adjusted for the effect of the other variable.

From the adjusted deviations the conclusion can be drawn that positive size effects are present up to 150 MW; between 151 and 450 MW there are no size effects, while small diseconomies of scale seem to be present with larger sizes than 450 MW. Moreover, younger vintages up to 1967 induce a higher fuel efficiency, whereas after 1967 there are no vintage effects. The *eta*- and *beta*-coëfficients are indications of the relative importance of the independent variables in explaining variations in the dependent variable.[42] From Table 2 it is evident that size and vintage are almost equally important in explaining

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[40] It should be noted that analysis of variance enables independent variables to be metric or nonmetric. See Kim and Kohout (1970, p. 399).

[41] These conclusions hold independent of the approach for analysis of variance that has been used (the classical experimental design, the hierarchical and the regression approach; see Kim and Kohout (1970, pp. 405–408)). F-values for size and vintage are 12.11 and 24.47 respectively, the critical F-value at the 1% level is 1.85 ($n_1 = 6; n_2 = 78$) for size and 2.02 ($n_1 = 4; n_2 = 78$) for vintage. Moreover with size the contrasts between category 1 and all other categories and between category 2 and 4 and 5 are significant, whereas with vintage only the contrasts between category 1 and all other categories are significant; see Scheffé (1959, pp. 68–72).

[42] See Kim and Kohout (1970, pp. 409–410).

TABLE 2 – MULTIPLE CLASSIFICATION ANALYSIS WITH FUEL EFFICIENCY AS THE DEPENDENT VARIABLE AND SIZE AND VINTAGE AS THE INDEPENDENT VARIABLES

	Deviations from the grand mean (= 0.36)		N
Categories of size	Unadjusted	Adjusted	
1. 0–50 MW	–0.08	–0.05	12
2. 51–100 MW	–0.03	–0.01	28
3. 101–150 MW	0.02	0.00	20
4. 151–200 MW	0.04	0.03	10
5. 201–300 MW	0.04	0.03	4
6. 301–450 MW	0.05	0.03	7
7. > 450 MW	0.04	0.02	8
(Eta and Beta)	(0.87)	(0.49)	
Categories of vintage			
1. < 56	–0.07	–0.04	28
2. 56–61	–0.00	0.01	16
3. 62–67	0.02	0.01	22
4. 68–75	0.04	0.02	24
5. > 75	0.05	0.02	4
(Eta and Beta)	(0.89)	(0.54)	
Multiple R squared (Multiple R)	0.891 (0.944)		

variations in fuel efficiency. Both variables together explain nearly 90 percent of the variations in fuel efficiency; see the value of R^2.[43]

Regression analysis

A more sophisticated way of investigating size and vintage effects on fuel efficiency is possible by means of regression analysis (see also note 23).

Several specifications of a functional relationship with fuel efficiency as the dependent variable and size and vintage as the independent variables have been taken into consideration. Both specifications used in previous studies on steam electric power generation[44] and commonly applied func-

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[43] Because of unequal cell frequencies there is no straightforward relationship between the *eta*-coëfficients and R^2; see Kim and Kohout (1970, p. 404).

[44] In this respect three specifications are relevant (the symbols of the variables are defined above; $a, b, c, d (i = 1, 2, 3)$ are the parameters to be estimated).

(1) $E = a_1 \, S b_1$ (estimations for each vintage group; see Komiya (1962, p. 159)).

(2) $E = a_2 (S)^{-1} + b_2$ (estimations for each vintage group; specification similar to the one used by Galatin (1968, p. 103)).

tional relationships for regression analysis, like the linear and log-linear specification, have been estimated. However, only the estimation results of the following specification will be presented:

$$E = a \cdot e^{bV} \cdot S^{c}$$

where E stands for fuel efficiency, V stands for vintage, S stands for size and a, b and c are parameters to be estimated.

There are two reasons for the choice of this specification. First, the estimation results, especially the value of R^2 and the t-values of the regression coefficients, are better than or equally as good as those of other specifications. Second, this specification enables a straightforward interpretation of the regression coëfficients; e.g. the vintage effect, b, is expressed as a growth rate and the size effect, c, can be interpreted directly as a size elasticity.

Estimations have been carried out for the whole sample and for different subsamples, each corresponding to a size or vintage category. The size and vintage categories have been chosen according to the categories of the multiple classification analysis (see Table 2). In Appendix B the estimation results are presented. The main conclusion from these outcomes is that only sizes below 150 or 200 MW and vintages up to 1967 can be meaningfully included in a sample for regression analysis. Vintages after 1967 or sizes above 200 MW do not yield statistically significant results with regard to their effects on fuel efficiency. This conclusion is in accordance with the implications from the multiple classification analysis.

In Table 3 the regression results are presented for small sizes (below 150 or 200 MW) and/or old vintages (up to 1967) on the one hand, and those for large sizes (over 150 or 200 MW) and/or recent vintages (later than 1967) on the other hand. One can see that for small sizes and/or old vintages the estimation results are satisfactory from a statistical point of view. It turns out that the regression coefficients hardly change when turbines between 150 and 200 MW are included in the sample. Up to 1967 the vintage effect on fuel efficiency is about 1 percent per year, the size elasticity is circa 0.12 for sizes below 200 MW. However, the results for large sizes and recent vintages are statistically poor; moreover, the sign of the regression coëfficient for the vintage variable is negative, although insignificant.[45]

(3) $E = a_3 S + b_3 S^2 + c_3 S^3 + d_3$ (estimation for the whole sample; specification similar to the one used by Wills (1977, p. 507)).

[45] It should be noted that the sample sizes of two subsamples do not add up to 89, the total sample size ($67 + 35 \neq 89$; $72 + 30 \neq 89$), because the subsamples are not mutually exclusive.

TABLE 3 – SIZE AND VINTAGE EFFECTS: REGRESSION RESULTS FOR SMALL SIZES AND OLD VINTAGES AND FOR LARGE SIZES AND YOUNG VINTAGES

Sample	Regression coefficients (t-values)			R^2	$\bar{R}^2$*	$\Gamma s/v$**
	Size (c)	Vintage (b)	Constant (lna)			
Sizes 0–150 MW or vintages up to 1967 ($N = 67$)	0.12 (8.31)	0.010 (8.74)	−2.18 (40.96)	0.88	0.87	0.68
Sizes 0–200 MW or vintages up to 1967 ($N = 72$)	0.11 (7.99)	0.0099 (8.56)	−2.14 (42.61)	0.88	0.87	0.72
Sizes > 150 MW or vintages after 1967 ($N = 35$)	0.031 (2.58)	−0.0021 (0.012)	−0.92 (11.36)	0.20	0.15	0.75
Sizes > 200 MW or vintages after 1967 ($N = 30$)	0.039 (3.00)	−0.0036 (1.64)	−0.86 (7.82)	0.28	0.22	0.79

* Adjusted R^2.

** Correlation coefficient between size and vintage.

4 CONCLUDING REMARKS

The following conclusions can be drawn from our empirical analysis of electricity generation in The Netherlands between 1955 and 1980.

1. Scale effects are present for turbines below 150 or 200 MW, whereas there is no significant difference in fuel efficiency for turbines between 200 and 650 MW. It should be noted that for technical reasons the best current unit thermal efficiency is about 42 to 45 percent.[45a]
2. For vintages up to 1967, positive technological change effects can be observed, but for turbines of later vintages there are hardly any differences in fuel efficiency.
3. Sizes and vintages of turbines are positively correlated, *i.e.* turbines of older vintages are generally of a small size and recently built turbines often have a large scale. However, there are no interaction effects between size and vintages with respect to fuel efficiency. So the influence of size on fuel efficiency does not diverge with the vintage of the turbine. An analogous conclusion can be drawn regarding the vintage effect on fuel efficiency with different sizes of the turbine.
4. Fuel-type (coal, oil, gas or a mixed category) does not have a significant influence on the fuel efficiency of turbines.

Evidently the effects of scale, vintage and fuel-type could only be studied with respect to fuel input. Similar effects on capital or labour input had to be left out of consideration, because the relevant data were not on hand.

The conclusions 1, 2 and 3 are in accordance with empirical studies on electricity generation in the United States. In comparing our results with those found by authors who used samples of units that are similar to ours with respect to size and vintage, we see that:

- Joskow and Mishkin, who only considered machines above 200 MW (vintages between 1952 and 1965), found small, although statistically insignificant scale and vintage effects in fuel efficiency.[46]
- Wills concluded to a size elasticity on fuel efficiency of 0.17 for the whole sample (average size 174 MW) and only 0.04 for sizes above 300 MW (vintages between 1947 and 1969).[47]
- and Cowing, who used data on turbines built between 1957 and 1965 with sizes up to 700 MW or more, has found a yearly fuel-augmenting technological change for total costs of 2 percent.[48]

[45a] Cowing (1974, p. 137); Stewart (1979, pp. 555–556).

[46] Joskow and Mishkin (1977, p. 724).

[47] Wills (1977, p. 508).

[48] Cowing (1974, p. 149).

Conclusion 4 about the influence of the fuel-type on fuel efficiency seems to be in constrast with conclusions found in American studies – see section 2.2 – although in a recent American study similar results have been found.[49]

In The Netherlands six units with capacities ranging from 320 to 640 MW came into operation during the years 1975 to 1978.[50] An interesting question can now be raised: why the Dutch electricity industry did not build turbines of 150 to 350 MW in this period? Evidently, from our empirical results the conclusion can be drawn that the latter units are not less fuel efficient than the larger machines that have been actually built. And an important advantage of smaller units is that, due to a shorter construction period and because of a shorter planning horizon, planning conditions are less severe, so that the flexibility of the investment decisions will be greater. Moreover, larger units often are more complex and will be more difficult to operate. Finally, the use of bigger units, which also break down more frequently, induces a higher demand for reserve capacity.[51]

Our study only dealt with fuel efficiency. However, decision making on the optimal size of turbines will also be based on other factors such as:

1. the relationship between capital costs and size. American authors are inclined to conclude that there are no economies of scale in capital input.[52]
2. the relationship between labour costs and size. Relatively strong scale effects of labour input have been found in some studies.[53] However, labour costs account only for about 10 percent of total costs.[54]
3. other factors, depending on the location of the plant.

In particular data on fuel prices and on the capital costs of the different turbines should be available in order to get an overall impression of the economies of scale and technological change. However, these data are not available.

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[49] Joskow and Mishkin (1977, p. 730).

[50] Vellema (1980, p. 877); Van Helden and Muysken (1980, p. 34).

[51] Van der Hoeven (1980); Abdulkarim and Lucas (1977). The phenomenon of availability and utilisation of turbines has been elaborated in Appendix C.

[52] Wills (1977, pp. 499, 506); Joskow and Mishkin (1977, p. 726).

[53] Wills (1977, pp. 508, 509); Joskow and Mishkin (1977, p. 724, 725).

[54] Cowing (1974, p. 137); Bakker (1980).

APPENDIX A

THE DATA USED

In Table A.1 the data which have been used for the estimations presented in section 3 are given. In this table the variables are defined as follows:

- ID = Identification of the turbine (ID = 1, 2, . . . 89); the order of the turbines is not systematic in whatever sense.
- Begin = the first-year data on fuel efficiency are available.
- End = the last-year data on fuel efficiency are available.
- Vintage = the vintage, *i.e.* the year of commissioning, of the turbine.
- Size = the size of the turbine in MW.
- Fuel eff. = the maximal fuel efficiency during the lifetime of a turbine (see below).
- Fuel type = the fuel type of the turbine (see section 3.1, where the numbers are explained).

For the following turbines a correction of the maximum fuel efficiency has been carried out (in section 3.1 the desirability of these corrections has been explained).

- ID = 17 : the maximum value of fuel efficiency only occurred once or twice, mostly under exceptional values of the hours worked.
- ID = 22 : see ID = 17.
- ID = 23 : see ID = 17.
- ID = 26 : see ID = 17.
- ID = 40 : during a relatively low number of years another fuel-type was present with a somewhat higher value of fuel efficiency.
- ID = 41 : see ID = 40.
- ID = 42 : see ID = 40.
- ID = 52 : see ID = 17.
- ID = 54 : see ID = 40.
- ID = 55 : see ID = 17.
- ID = 56 : see ID = 17.
- ID = 58 : see ID = 17.
- ID = 63 : see ID = 17.
- ID = 64 : see ID = 17.
- ID = 65 : see ID = 17.
- ID = 66 : see ID = 17.
- ID = 84 : see ID = 17.

TABLE A.1 – THE DATA USED (AN "*" HAS BEEN PLACED WITH THOSE TURBINES FOR WHICH A CORRECTION OF MAXIMAL FUEL EFFICIENCY HAS BEEN CARRIED OUT)

ID	Begin	End	Vintage	Size	Fuel eff.	Fuel type	ID	Begin	End	Vintage	Size	Fuel eff.	Fuel type
1	68	76	67	63	0.3622	6	46	76	79	75	269	0.4037	7
2	68	76	67	165	0.4209	7	47	59	79	58	66	0.3645	6
3	76	76	75	540	0.4226	7	48	59	79	58	66	0.3676	1
4	76	76	75	540	0.4160	7	49	70	79	66	166	0.3984	7
5	64	76	63	150	0.3908	1	50	70	79	68	130	0.4063	7
6	72	76	71	320	0.4345	7	51	54	78	52	58	0.3246	1
7	73	76	72	320	0.4303	7	52	54	76	53	30	0.2750	1*
8	66	76	65	158	0.4160	7	53	59	76	58	32	0.3273	6
9	69	76	68	158	0.4199	7	54	54	76	53	30	0.2770	1*
10	60	79	59	80	0.3811	1	55	51	63	35	42	0.2440	2*
11	62	79	61	130	0.4037	3	56	56	79	55	58	0.3200	1*
12	70	79	55	60	0.3239	7	57	70	79	62	125	0.3601	7
13	70	79	55	60	0.3306	7	58	70	79	64	110	0.3410	7*
14	70	79	61	120	0.3711	7	59	71	79	70	193	0.4089	7
15	70	79	64	135	0.3811	7	60	54	76	53	30	0.2800	1
16	73	79	72	322	0.4045	7	61	59	76	58	32	0.3273	6
17	64	78	63	125	0.3860	3*	62	55	76	54	30	0.2900	6
18	67	78	66	125	0.4014	7	63	51	63	35	42	0.2430	1*
19	67	78	66	125	0.4035	7	64	56	79	55	58	0.3200	1*
20	71	78	70	130	0.3977	7	65	70	79	61	125	0.3570	7*
21	71	78	70	130	0.3962	7	66	70	79	65	110	0.3410	7*
22	62	76	60	60	0.3420	7*	67	71	79	70	193	0.4089	7
23	66	76	65	67	0.3370	7*	68	62	76	61	86	0.3820	2
24	75	76	74	328	0.4052	6	69	61	76	60	86	0.3820	2
25	76	76	75	328	0.4064	6	70	51	75	46	50	0.3127	1

TABLE A.1 (contd)

ID	Begin	End	Vintage	Size	Fuel eff.	Fuel type	ID	Begin	End	Vintage	Size	Fuel eff.	Fuel type
26	58	79	57	62	0.3510	3*	71	53	76	52	58	0.2957	1
27	60	79	59	81	0.3575	3	72	54	76	53	58	0.2957	1
28	64	79	63	123	0.3771	7	73	55	76	54	58	0.2957	1
29	64	79	63	123	0.3771	7	74	53	76	52	53	0.2989	1
30	69	79	68	185	0.3926	7	75	54	76	53	55	0.2989	1
31	70	79	69	185	0.3924	7	76	56	76	55	53	0.3336	1
32	74	79	73	465	0.3898	7	77	56	76	55	55	0.3336	1
33	65	79	64	66	0.3470	2	78	55	77	54	52	0.2945	3
34	67	79	66	132	0.3975	3	79	55	78	53	52	0.2945	3
35	70	79	69	132	0.4081	7	80	55	75	54	24	0.2834	1
36	57	79	56	120	0.3742	3	81	55	75	54	24	0.2834	3
37	61	79	60	177	0.3964	2	82	59	79	58	33	0.3178	2
38	66	79	65	220	0.4100	2	83	66	79	65	80	0.3916	2
39	67	79	66	220	0.4176	6	84	69	79	68	77	0.3822	7*
40	72	79	71	410	0.4000	6*	85	70	79	69	77	0.3822	7
41	73	79	72	410	0.4070	6*	86	77	78	77	611	0.4149	6
42	70	79	66	190	0.4080	7*	87	78	79	78	527	0.4040	7
43	70	79	69	233	0.4039	7	88	77	79	77	640	0.4139	7
44	70	79	67	125	0.3634	7	89	78	79	78	640	0.4089	7
45	75	79	74	460	0.3993	6							

APPENDIX B

SIZE AND VINTAGE EFFECTS ON FUEL EFFICIENCY: REGRESSION RESULTS FOR THE WHOLE SAMPLE AND FOR DIFFERENT SUBSAMPLES ACCORDING TO SIZE OR VINTAGE CATEGORIES

In Table B.1 the regression results are presented. The specification of the relationship between fuel efficiency on the one hand and size and vintage on the other hand has been introduced in section 3.2.

From the multiple classification analysis we know that size classes of 0–50 MW, 51–100 MW, 101–150 MW and 151–200 MW induce different values for fuel efficiency, whereas there are almost no such differences between 151–200 MW and sizes above 200 MW. Analogously vintage classes up to 1967 bring about increasing values for fuel efficiency, but after 1967 there are hardly any vintage effects. According to this classification, subsamples are defined, for each of which estimates have been carried out.

The results of these estimations (see Table B.1) are satisfactory in a statistical sense for size categories below 150 MW and for vintage categories up to 1967, though size and vintage are strongly intercorrelated. Vintage effects after 1967 and size effects of sizes above 150 MW are not present, as can be concluded from the low value of R^2 and the relatively low t-values belonging to the regression coefficients.

If we compare the size effects of the vintage categories before 1967 with those effects of the size categories below 150 MW, the former ones are far bigger than the latter ones. The reason for this difference is due to differences in the coefficients of variation of the size variable, as presented in Table B.2. The average coefficient of variation for the three size categories is 0.155, whereas this coefficient is 0.359 for the three vintage categories (the average coefficient of variation of fuel efficiency, the dependent variable, is almost the same, respectively 0.083 and 0.074). It is plausible to prefer the estimation results which are based on a larger variation of the size variable, *i.e.* the results of the vintage categories. These results are similar to those presented in section 3.2, Table 2.

For each size or vintage category both independent variables have been taken into consideration. However, if the t-value of the size variable was less than 2 in a size category, the vintage variable was considered to be the only independent variable; analogously, if the t-value of the vintage variable within a vintage category was less than 2, estimations have been carried out with the size variable only; see Table B.1.

TABLE B.1 – REGRESSION RESULTS FOR THE WHOLE SAMPLE AND FOR DIFFERENT SUBSAMPLES

Sample	Regression coefficients (t-values)					
	Size	Vintage	Constant	R^2	$\bar{R}^2$*	Γ s/v**
Total (N = 89)	0.049 (3.19)	0.010 (6.72)	−1.87 (36.78)	0.79	0.79	0.84
Size: 0–50 MW (N = 12)	0.32 (5.13)	0.016 (9.35)	−3.15 (11.25)	0.91	0.89	−0.67
Size: 51–100 MW (N = 28)	0.37 (4.95)	0.0067 (2.92)	−3.02 (12.66)	0.81	0.80	0.70
Size: 101–150 MW (N = 20)	0.52 (3.68)	0.0042 (1.52)	−3.75 (5.58)	0.53	0.48	0.22
Size: > 150 MW (N = 29)	0.00087 (0.041)	0.00050 (0.23)	−0.94 (11.34)	0.010	–	0.86
Vintage: < 56 (N = 23)	0.14 (4.80)	0.011 (6.36)	−2.30 (16.94)	0.77	0.75	0.076
Vinage: 56–61 (N = 16)	0.12 (6.57)	–	−1.52 (19.74)	0.76	0.74	(0.48)
Vintage: 62–67 (N = 22)	0.15 (4.79)	–	−1.67 (11.24)	0.53	0.51	(0.082)
Vintage: > 67 (N = 28)	0.023 (2.80)	–	−1.03 (21.96)	0.23	0.20	(0.85)

* Adjusted R^2.

** Correlation coefficient between size and vintage.

TABLE B.2 – COEFFICIENTS OF VARIATION CONCERNING FUEL EFFICIENCY, SIZE AND VINTAGE FOR THE WHOLE SAMPLE AND FOR DIFFERENT SUBSAMPLES

Sample	Coefficient of variation*		
	Fuel efficiency	Size	Vintage
Total ($N = 89$)	13.1	94.6	13.8
Size: 0–50 MW ($N = 12$)	9.9	23.1	15.9
Size: 51–100 MW ($N = 28$)	9.6	16.6	8.9
Size: 101–150 MW ($N = 20$)	5.5	6.8	5.4
Size: > 150 MW ($N = 29$)	2.9	8.4	6.4
Vintage: < 56 ($N = 23$)	8.4	26.9	10.8
Vintage: 56–61 ($N = 16$)	6.9	48.0	2.7
Vintage: 62–67 ($N = 22$)	6.9	32.9	2.3
Vintage: > 67 ($N = 28$)	3.4	11.3	4.5

* The coefficient of variation is defined as the standard deviation divided by the mean; in the table the result of this calculation is multiplied by 100.

APPENDIX C

AVAILABILITY AND UTILISATION OF TURBINES

In Table C.1 the average availability and utilisation rate of turbines in different size/vintage categories are presented. The availability rate is defined as the quotient of the hours worked and the maximum number of hours per year (= 8760) per turbine. The utilisation rate has been computed as the actual production divided by the maximum production during the hours worked per year per turbine. Both variables are defined as a yearly average per turbine over three years, *i.e.* the first year of operation and the two succeeding years. These three years have been chosen, because they approximate the circumstances of a normal operation of a turbine; comparison between different turbines is then possible. If only data on one or two first years of operation are available, the average availability and utilisation rate have been computed for one or two years respectively. If data on the first three years of operation of a turbine are not on hand, this turbine has been left out of consideration.

In each capacity/vintage cell of Table C.1 the average availability and utilisation rate are presented on the left- and right-hand side respectively; the number of turbines, which underlies these averages, has been presented between brackets. The categorisation of size and vintage classes is similar to Table 1, except that size categories 0–50 and 50–100 MW and vintage

TABLE C.1 – THE AVERAGE YEARLY AVAILABILITY AND UTILISATION RATE DURING THE FIRST THREE YEARS OF OPERATION FOR TURBINES IN DIFFERENT CAPACITY/VINTAGE CATEGORIES

Vintage/ Capacity (in MW)	< 62	62–67	68–75	> 75
0–100	0.709 0.722 (16)	0.829 0.686 (4)	0.833 0.837 (2)	
101–150	0.776 0.709 (4)	0.821 0.719 (11)	0.869 0.780 (4)	
151–200	0.752 0.644 (1)	0.719 0.732 (5)	0.835 0.743 (5)	
201–300		0.834 0.620 (2)	0.809 0.659 (2)	
301–450			0.742 0.741 (7)	
451–700			0.704 0.691 (4)	0.553 0.568 (4)

categories < 56 and 56–62 have been taken together, because small and early-built turbines often had to be left out of consideration due to the fact that no data on the first years of operation were available.

From Table C.1 one sees that within each size category, recently built turbines show a higher availability and utilisation rate than older turbines, except for the size category 450–700 MW with relatively low rates for the most recently installed machines. Within the vintage categories the pattern is somewhat different: for turbines up to 300 MW the differences between availability and utilisation rates are small, whereas for turbines of 300 MW or larger, significantly lower rates can be observed.

Hence, the conclusion can be drawn that the biggest units (with a capacity of 300 MW or more) have relatively low availability and utilisation rates. This conclusion is rather amazing if one takes into consideration that large turbines, especially when they are part of the production process together with small units, are planned for base-load production and therefore should have a high rate of availability and utilisation. We investigated this phenomenon in a more sophisticated way; see Van Helden and Muysken (1981).

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Summary

ECONOMIES OF SCALE AND TECHNOLOGICAL CHANGE IN ELECTRICITY GENERATION IN THE NETHERLANDS

An important characteristic attributed to electricity production has been the existence of economies of scale. Economies of scale are said to be partly determined by fuel input, e.g. large electricity generating units have a greater fuel efficiency than small ones. This article shows, using Dutch data, that scale effects in fuel efficiency are only present for units below 200 MW. Fuel efficiency hardly differs for units of a capacity between 200 and 600 MW. An analogous conclusion is drawn on the relation between fuel efficiency and vintage: technological improvements occur until 1967 and are absent thereafter.