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5 Electric Utility Generating Equipment

5.1 Introduction

Electric utility generating equipment is the second case study of the methodology proposed in chapter 2. Like the commercial aircraft that were the subject of the previous chapter, data availability and the importance of energy as a factor input justify the choice of electric generating equipment for detailed scrutiny. As in the case of aircraft, government regulation of the industry using the equipment provides a wealth of data on the performance of equipment, as well as its operating characteristics. Another similarity to aircraft is the sequence of rapid technical improvements in the first part of the postwar era, followed by a sharp slowdown in the pace of improvements just as the oil shocks boosted the price of energy inputs. As for aircraft, most of the rapid improvements and the subsequent slowdown were achieved by the equipment manufacturer, yet the user industries (airlines and electric utilities) receive credit for the earlier productivity advances and the later slowdown in official productivity data. The main difference between the utility and the airline examples, as we shall see, is that there has been negative efficiency improvement along several dimensions in the electric utilities, while airline efficiency has continued to improve, albeit at a slower pace.

The electric utility industry has attracted a large number of studies by industrial organization economists interested in issues raised by regulation (e.g., Joskow and Schmalensee 1983), as well as by econometricians interested in using the extensive available data to test hypotheses about factor and product demand.[1] More closely related to this study of equipment prices are the studies that attempt to compile quality-adjusted price indexes for the

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[1] Examples of econometric studies include Bushe (1981), Christensen and Greene (1976), Nerlove (1963), and Wills (1978). A survey is provided by Cowing and Smith (1978).

equipment used in the production of electricity by Barzel (1964), Ohta (1975), and Wills (1978). While these studies cover only the earlier part of the 1947–82 sample period, their results are compared with mine for overlapping intervals in a later section of this chapter.

The basic data source for this chapter is a set of reports submitted by electric utilities to the Federal Energy Administration and its predecessor agencies on equipment costs, quantities and costs of variable factor inputs, and output for each electric generating plant. Coverage is limited to fossil-fueled steam-electric generating plants. Excluded are gas turbine and nuclear generation equipment, as well as equipment involved in the distribution and marketing of electricity. However, this limited coverage still includes the equipment that produces the majority of U.S. electricity, and the dominant role of fossil-fueled generating equipment in causing the slowdown of productivity growth in the electric utility industry is seen in the similarity of the path of postwar productivity growth for the plants covered in this chapter and for the electric utility industry as a whole (see tables 5.2 and 5.3 below).

Section 5.4, after a brief overview of data on changes in productivity and prices of output, inputs, and equipment for the electric utility industry as a whole, presents a display of data on the same variables for the sample of fossil-fuel steam generating plants. The task of creating quality-adjusted price indexes for equipment begins in section 5.5, where hedonic regression equations are run for a cross section of new plants that explain equipment prices in adjacent years ("vintages") by a set of variables that includes equipment characteristics and dummy variables for particular vintages. Then section 5.7 provides estimates of the net revenue provided by each vintage of equipment, so that indexes of quality-adjusted price changes can be constructed from ratios of net revenue to equipment cost, using the methodology of chapter 2.

The implementation of the quality-adjustment methodology in this chapter is more straightforward than in the chapter on commercial aircraft. One simplifying factor is that electricity is a homogeneous commodity, and we do not have to speculate about changes in its quality. More important, electric generating plants are all different, and there is no analogy here to the "model runs" of tens or hundreds of identical units of a particular aircraft model. Thus, in contrast to the involved analysis of the net revenue provided by individual aircraft models in chapter 4, in this chapter the estimates of net revenue are based on simple averages of performance for all units of a given vintage.

5.2 The Technology of Electricity Generation

Although electric utilities are monopolists in the local markets they serve, the aggregate number of these individual monopolies is substantial, in contrast to the very small number of major producers of generating equipment. The relatively large number of buyers in relation to sellers is even more evident when the existence of a substantial export market for equipment is taken into account.[2] Thus, utilities can accurately be described as price takers in the market for new equipment, and they are also ''quality takers'' in the sense that their choice set is constrained by whatever price-quality combinations are offered by equipment manufacturers on the market at any given time. The R&D expenditures that (at least in the past) have improved efficiency and productivity have taken place in the manufacturing sector, not in the utility industry.

The basic output of the utility industry can be expressed as a stock or a flow. The production process generates ''electric power,'' an instantaneous concept, and the capacity of a generating unit is measured by the amount of electric power that it can produce at a moment in time, measured in kilowatts (KW) or megawatts (1,000 kilowatts, or MW). ''Electricity,'' the flow measure, is the total energy that is produced by creating electric power for a duration of time and is measured in kilowatt hours (kWh). The production process involves the transformation of the internal energy in a fuel source into electrical energy. It takes place in a ''power generation cycle'' that can be divided into four stages: fuel combustion, steam generation, steam expansion, and power generation. A power generation ''unit'' operates independently of any other units at a given plant location and consists of a boiler to burn the fuel and to generate and expand the steam, and a turbo-generator that converts high-pressure steam into electric energy through the rotary motion of a turbine shaft. A condensor converts the steam into water to complete the cycle. The entire unit is called a ''boiler-turbo-generator,'' or BTG unit. For the purposes of this chapter, the important aspect of the technology is the jointness of production by the BTG unit, making it impossible to develop price indexes for boilers and turbo-generators separately. Although individual units can be started and stopped independently, the plant is normally treated as the relevant economic entity for regulatory, accounting, and managerial purposes, and the data set, where the plant is the observation, contains no information on the characteristics of the individual units within the plant other than their number.

A central measure of the efficiency of the technical transformation process is the ''heat rate'' of the cycle, the ratio of input in British thermal units to one kWh of output. The higher the heat rate, the more fuel is being consumed in the production of a given amount of electricity, and the less efficient is the generation process. Although all the data on fuel efficiency in the industry appear to be expressed in terms of the heat rate, a concept that

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2. Ohta (1975, 7) cites evidence that in 1957 about 80 percent of the total boiler supply was provided by two firms, Combustion Engineering and Babcock & Wilcock, and that in 1957–59 almost all the turbogenerators were produced by General Electric, Westinghouse, and Allis-Chalmers.

seems to be expressed in more natural units is "thermal efficiency," which represents the fraction of a unit's efficiency as related to a theoretical and unattainable standard of unity.[3] Thus, in assessing changes in the quality of BTG units, heat rate or thermal efficiency is as central a concept as is labor productivity in other applications.

Technical change in the design of BTG units has been aimed primarily at improving the thermal efficiency of the generating cycle by increasing the temperature to which the steam is heated, increasing the pressure of the steam entering the turbine, and reducing the heat that is transferred out of the cycle in the condenser. The technical design frontiers have been limited by the ability of boilers to withstand high temperatures and pressures, and the frontier has been pushed out by advances in metallurgy involving the development of high-temperature steel alloys. In 1948, three-quarters of all planned installations were designed for an operating pressure of under 1,200 psi (pounds per square inch) and over 80 percent for a temperature under 1,000° F. By 1977, over 80 percent were designed to operate at pressures of 2,400 psi and above, and virtually all had temperature ratings above 1,000° F (Bushe 1981, 44–46).

Another improvement was the addition of reheat cycles, which involve draining off steam at an intermediate stage and reheating it to raise the average temperature of the cycle and reduce the moisture content of the steam. As we shall see below, thermal efficiency and labor productivity improved through the mid-1960s and then deteriorated. This is related to the fact that the shift to higher temperatures and to reheat cycles was largely completed during the 1948–57 decade, with little further change thereafter, although the increase in pressure rating continued until the mid 1970s. Another technical development in the 1960s was the "supercritical" boiler (achieving a pressure above 3,200 psi). After reaching a 30 percent share in new installations in the late 1960s, the share of supercritical units fell to 13 percent in 1977, a phenomenon that has been variously attributed to an increase in the cost of capital, uncertainty about future demand growth, and (more important in assessing the quality of capital goods) an unexpected increase in the maintenance burden required by supercritical units.

Throughout the postwar period, the average scale of BTG units has increased, with 70 percent of new units rated below 50 MW in 1948, and 66 percent above 500 MW in 1977. Increased scale has also been a source of improved thermal efficiency, since many of the technical improvements required greater capital expenditures, the expense of which could be partially offset by increased scale. Engineers use a "six-tenths" rule for approximating the additional cost of a capacity increase; that is, a 1 percent increase in capacity increases capital cost by 0.6 percent, reflecting the geometric fact

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[3] Because the energy contained in one kWh is 3,415 BTU, thermal efficiency equals 3,415 divided by the heat rate, or TE = 3,415/HR.

that a 1 percent increase in the volume of a sphere increases its surface area by about 0.6 percent (Moore 1959). Cowing (1970) has dubbed this interaction between increasing scale and technical improvements "scale-augmenting technical change," but it is important to note that its benefits were exhausted in the first half of the postwar era. As Wills (1978, 500) demonstrates, there is little further improvement in thermal efficiency as unit sizes increase beyond 250 MW, and, indeed, after increasing from 21.7 percent in 1948 to 32.6 percent in 1963, thermal efficiency in new plants showed no increase at all from 1963 to 1985.[4]

While economies of scale with respect to thermal efficiency may have been exhausted in the 1950s, as the average size of new units advanced beyond the range of 150–250 MW, there is no evidence that there was a similar termination of improvements in labor productivity due to increased scale. Wills (1978, 501) plots the number of employees against plant capacity and finds increasing returns to scale at all plant sizes. However, in parallel research on labor productivity, I have found that the steady downward shift in labor requirements over new plant vintages continued only through 1968 and then reversed itself from 1968 to 1980 (Gordon 1985).

5.3 Postwar Performance of the Electric Utility Industry

The data used in this chapter cover only a segment of the capital equipment of the electric utility industry, the boilers and turbine generators that produce electricity with fossil fuel ("steam plants"). Excluded are not only nuclear and hydro plants, but also equipment used in transmission, distribution, and bill collection. As shown in table 5.1, steam plants account for roughly two-thirds of electric utility operating expenses (excluding purchased power and taxes), but for just one-third of the book value of the capital stock in place ("plant in service"). Of the $88.3 billion of steam plant in service, $65.3 billion consists of the boiler and turbogenerator equipment with which we are concerned in this chapter, and the remainder consists of land, structures, and auxiliary electrical equipment.

Corresponding to the fact that steam plants account for much less of capital than of operating expenses, the ratio of capital to operating expense is lower for steam plants than for the other major types of capital—nuclear plants and transmission/distribution equipment. Unfortunately, there is no known source of price data for transmission and distribution equipment by vintage, and so it is not possible to extend the coverage of this chapter to that large category of equipment used in the electric utility industry.

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[4] U.S. Department of Energy (1987, table 14) shows that heat rate did not move outside the rate 32.6–33.0 percent over the entire period between 1963 and 1985.

Table 5.1 **Distribution of Operating Expenses and Plant in Service, Electric Utility Industry, 1983**

	Operating Expenses		Plant in Service		Ratio of Capital to Operating Expense
	$Billion	(%)	$Billion	(%)	
Steam plants:	39.3	(66.8)	88.3	(35.6)	2.2
Fuel	34.0				
Other	5.9				
Land			0.6		
Structures			14.5		
Boiler equipment			48.0		
Turbogenerators			17.3		
Electric and other			8.0		
Nuclear plants	4.1	(6.9)	30.4	(12.2)	7.4
Hydro plants	0.3	(0.5)	6.1	(2.5)	20.3
Other plants (gas turbine, etc.)	0.9	(1.5)	4.5	(1.8)	5.0
Transmission	1.2	(2.0)	38.0	(15.3)	31.7
Distribution	4.0	(6.7)	73.3	(29.5)	18.3
Customer accounts and general administration	9.3	(15.6)	7.4	(3.0)	0.8
Total[a]	59.7	(100.0)	248.0	(99.9)	4.2

Source: U.S. Department of Energy (1983, tables 3 and 2).
[a]Excludes purchased power.

Table 5.2 displays the growth rates over five-year intervals of data on the performance of the utility industry as a whole. The data are obtained mainly from the NIPAs. Unfortunately, the NIPA data include not just electric utilities but also gas and "sanitary services" utilities.[5] In table 5.2 we observe that, while compensation per full-time equivalent (FTE) employee accelerates after 1967, output per FTE employee displays a steady deceleration throughout the postwar period. This pattern of a steady deceleration in productivity growth (with no apparent breaks) contrasts with the airline industry (table 4.1), where there is a sharp break before and after 1972.

The difference between per-employee compensation and output is unit labor cost, and in row 3 this exhibits a small negative growth rate through 1967, followed by a jump in each of the last three periods. The price of coal, represented by the PPI shown in row 4, exploded in the 1967–72 period, well before the first OPEC oil shock, and it seems remarkable that the rate of increase in the price of electricity during the 1967–72 period should have remained so far below the increase in the price of coal.[6] During 1972–77, the rate of increase in the price of electricity was in between that for unit

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[5] In 1983, there were 513,200 employees in investor-owned electric utilities (Edison Electric Institute 1984, table 90), as compared to 875,000 in the electric, gas, and sanitary category of the national accounts (NIPA, table 6.7B), or 59 percent.

[6] In 1980, coal was the fuel used for 66 percent of the electricity generated by fossil-fuel steam plants. Gas (20 percent) and oil (14 percent) account for the remainder.

Table 5.2 **Utility Prices, Costs, and Productivity Annual Growth Rates for Five-Year Intervals, 1947–82**

	1947–52 (1)	1952–57 (2)	1957–62 (3)	1962–67 (4)	1967–72 (5)	1972–77 (6)	1977–82 (7)	1947–86 (8)
1. Compensation per FTE employee	7.25	5.46	4.93	5.63	7.57	9.36	9.67	6.95
2. Output per FTE employee	8.01	6.09	5.77	4.57	3.76	1.51	−1.11	4.05
3. Unit labor cost	−0.76	−0.63	−0.84	−0.04	3.81	7.85	10.78	2.90
4. Price of coal	4.31	2.74	−0.82	1.31	14.15	14.97	6.55	5.83
5. Price of electricity	0.76	0.76	0.85	−0.02	3.52	9.95	11.03	3.75
6. PPI used for PDE steam turbine generators	4.09	9.65	−1.79	2.35	4.64	10.15	8.37	5.35
7. GNP deflator	3.18	2.34	1.67	2.30	4.80	6.96	8.12	4.20
8. Real price of coal	1.13	0.40	−2.49	−0.99	9.35	8.01	−1.57	1.63
9. Real price of electricity	−2.42	−1.58	−0.82	−2.28	−1.28	2.99	2.91	−0.45
10. Real price of equipment	0.91	7.31	−3.46	0.05	−0.16	3.19	0.25	1.15

Sources by row: (**1, 2**) Compensation from NIPA, table 6.5A, row 49. Full-time equivalent (FTE) employees, table 6.8A, row 49. Output from table 6.2, row 15. (**3**) Row 1 minus row 2. (**4**) PPI index 05-1. (**5**) NIPA, table 7.12, row 50. (**6**) PPIs used by NIPA to deflate steam turbine generators: 1947–69: 11-73-01-27, "steam turbine generator set"; 1969–82: 11-73-02, "generators and generator sets." (**7**) NIPA, table 7.1, row 1. (**8**) Row 4 minus row 7. (**9**) Row 5 minus row 7. (**10**) Row 6 minus row 7.

Note: NIPA indexes referenced here refer to the numbering system prior to the 1986 benchmark revision.

labor cost and for coal, while after 1977 inflation in electricity prices exceed that in both unit labor cost and coal.

Row 8 computes a "real price of coal" as the difference between the growth rates of the nominal price of coal in row 4 and the GNP deflator in row 7. On average, the real price of coal increased over the postwar period, but this average behavior disguises marked shifts between the 1947–57 decade in which the real price of coal increased slightly, the 1957–67 decade in which a modest decline was observed, the 1967–77 decade in which the real price of coal increased sharply, and the final 1977–82 period in which the real price of coal, somewhat surprisingly, registered a decrease. There were fewer twists and turns for the real price of electricity, as shown in row 9. A continuous decrease occurred from 1947 through 1972, followed by a substantial increase during the 1972–82 decade.

The last piece of information contained in table 5.2 concerns the main topic of this chapter, the price of equipment used by the electric utility generating industry. Expenditures by the utility industry on equipment purchases are deflated in the NIPA by the PDE deflator for "engines and turbines." In recent years, roughly two-thirds of the weight for this PDE component deflator, presumably that accounted for by electric utility spending on new turbine generators, is attributed to the six-digit PPI commodity index for "generators and generator sets" (11-73-01). This, in turn, is based mainly on an eight-digit commodity index for "electric generating plant" (110-125 KW). The specification of this commodity index indicates that it is a gasoline or diesel water-cooled engine, not a steam turbine generator. In contrast, the PDE deflator for generators during the period 1947–69 is based on the 11-73-02-27 index for "steam turbine generator set," an index that was discontinued after 1969. The reason for discontinuance was doubtless the highly atypical small size of the unit priced for the index, since the specification refers to a generator of thirty to forty MW. In contrast, the average size of a new unit in my sample as long ago as 1953 was 118 MW, and by 1967 this average unit size had grown to 530 MW. Assuming that the PPI index for steam turbine generators was discontinued because the unit had become obsolete and was no longer manufactured, it is somewhat surprising that this index was not replaced with one for the typical large unit. Instead, since 1969 neither the PPI nor the PDE deflator have contained any information at all on the prices of steam turbine generators, nor has the PDE deflator been retrospectively revised to adjust for the obvious flaws in the pre-1970 PPI.[7]

The rate of change of the two linked PPI indexes that are used to deflate electric utility generating equipment in NIPA PDE is shown in nominal terms in row 6 of table 5.2 and in real terms in row 10. The most rapid real increase in the real price of equipment occurred in the 1952–57 interval, the period of the electrical equipment conspiracy. There was a modest real decline between 1957 and 1967, followed by a real increase in equipment prices thereafter, with a significant real increase occurring in the period 1972–77. On average, there was an increase in the real price of equipment over the full 1947–82 postwar period.

5.4 Characteristics of the Sample of Generating Plants

Numerous interesting features of the data set are summarized in table 5.3, where the top section shows plant means, the middle section exhibits selected ratios, and the bottom section provides comparisons with the aggregate industry indicators reviewed above in table 5.2. The selected years are chosen to correspond to the years in table 5.2, except for the initial (1948) and terminal (1983) dates, which are dictated by the span of the data. Each cell contains two numbers, the top number indicating the mean for all plants in the sample in a given year, and the bottom in parentheses indicating the mean for new plants built in that year and the two successive years. New plant means are shown for three years rather than one to smooth out erratic

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[7] Information on the history of PPI specifications within the 11-73-02 commodity group was provided in a letter dated 14 May 1979 to me from John Early, chief of the Division of Industrial Prices and Price Indexes of the BLS.

Table 5.3 **Basic Characteristics of Plant Sample Means for All Plants (new plants in parentheses)**

	1948	1952	1957	1962	1967	1972	1977	1980	1983
Number of plants in sample (new plants per year)	55	105	133	179	206	236	226	280	186
	(39)	(29)	(23)	(19)	(15)	(28)	(26)	(11)[a]	
Plant means:									
1. Capacity (MW)	148	167	244	348	460	630	835	847	1,131
	(87)	(184)	(221)	(349)	(661)	(850)	(891)	(878)	
2. Output (million kWh)	817	896	1,278	1,623	2,275	3,003	3,708	3,544	4,519
	(478)	(991)	(1,218)	(1,788)	(2,979)	(3,139)	(3,186)	(2,463)	
3. Employees (56)	161	135	126	112	110	120	139	171	215
	(49)	(69)	(59)	(59)	(75)	(107)	(184)	(117)	
4. Maintenance cost ($million)	0.41	0.37	0.47	0.57	0.85	1.74	4.3	6.7	10.4
	(0.08)	(0.20)	(0.20)	(0.40)	(0.75)	(1.77)	(3.9)	(3.1)	
5. Fuel cost ($million)	3.4	3.5	4.1	4.7	6.2	12.6	49.3	73.9	107.5
	(1.4)	(2.6)	(3.3)	(4.2)	(6.7)	(14.3)	(37.3)	(45.2)	
6. Equipment cost ($million)	10.4	15.7	24.0	36.7	46.2	66.9	122.1	139.4	217.1
	(8.3)	(20.6)	(23.9)	(38.7)	(55.6)	(123.1)	(228.7)	(320.1)	
Ratios:									
7. Utilization rate (percent)	66.1	64.2	57.8	50.5	56.0	56.0	50.1	45.0	44.6
	(64.6)	(65.5)	(65.1)	(60.5)	(55.4)	(43.9)	(42.2)	(33.9)	
8. Output/employee (million kWh/employee)	6.0	7.9	12.1	15.9	22.6	27.6	30.0	23.6	28.5
	(8.2)	(14.2)	(22.5)	(28.9)	(39.7)	(31.2)	(19.0)	(25.3)	
9. Maintenance cost/ouptut ($/thousand kWh)	0.49	0.45	0.52	0.49	0.47	0.70	1.40	3.9	3.2
	(0.25)	(0.23)	(0.21)	(0.23)	(0.24)	(0.60)	(1.55)	(1.63)	
10. Fuel cost/output ($/thousand kWh)	4.3	3.5	3.6	3.2	3.0	4.6	14.9	27.3	28.9
	(3.2)	(2.8)	(2.8)	(2.7)	(2.5)	(5.5)	(13.8)	(20.6)	
11. Equipment cost/capacity($/kw)	78	99	104	108	104	109	140	161	187
	(116)	(104)	(120)	(115)	(89)	(137)	(243)	(346)	
Indexes (1972 = 100):									
12. Row 9/industry wage rate	(164)	(80)	(114)	(69)	(58)	(100)	(165)	(105)	
13. Row 10/price of coal	(134)	(121)	(116)	(102)	(87)	(100)	(124)	(127)	
14. Row 11/PPI for equipment	(219)	(160)	(114)	(120)	(83)	(100)	(107)	(100)	

Note: New plant means in parentheses refer to the average of the vintage indicated by the column label plus the two succeeding vintages, e.g., the means shown for new plants for 1948 actually include the three years 1948–50.

[a] The last three years have been grouped for the means of new plants.

fluctuations in the means attributable to the small number of plants built in each year, and the figures shown for all new plants refer to the first complete year of operation, that is, the year after the year of initial operation that establishes a plant's "vintage." Thus, the new plant means in the column labeled "1948" refer to plants of vintage 1948–50 as operated during the years 1949–51.

In 1980, the sample contained 280 plants, and this coverage represents 30 percent of all fossil steam plants in the United States, but 55 percent of the capacity. The relation between the total industry and the sample is as follows for 1980.[8] The ratio of capacity in the sample to capacity in the total industry has gradually increased over time, from roughly 20 percent in the late 1940s, to 30 percent in the early 1960s, to over 50 percent by the end of the 1970s.[9] The book value of equipment investment in the sample rose from $0.6 billion in 1948 to $40.1 billion in 1980.

Throughout its history, the electric generating industry has been characterized by increasing scale. For new plants, the mean size increased from 100 MW in 1948–50 to 878 MW in 1980–83.[10] Thus, one would expect that the mean size for new plants would always exceed the mean size for the stock of existing plants. This does not always occur in row 1 of table 5.3, because some of the older plants contain added units that were installed subsequently to initial operation. The fact that a plant can contain more than one unit, and that in some cases all units are not installed simultaneously, is the main defect of this data set, since the date of a plant's "vintage" does not uniquely identify the date of installation of all its units. This limitation does not, however, affect the results reported in this chapter, which are based entirely on new plants.

Just as plant capacity increases over time, so does plant output. However, an interesting pattern is evident in the behavior of plant utilization, calculated as output divided by capacity times 8,760 (the number of hours in a year). As shown in row 7, the utilization rate of all plants fell gradually throughout the postwar period. One important cause for this overall downtrend in utilization has nothing to do with the quality of generating plants, and this is the change in seasonal patterns associated with the development and spread of air conditioning (the difference in the average summer and winter peak load is greater now than in the late 1940s, when the winter peak load was somewhat higher owing to the need for more lighting

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[8] Figures for the total U.S. industry are from U.S. Department of Energy (1983, 3).

[9] The data set for 1948–71 was obtained from Thomas Cowing and was developed by an unknown method of sampling the available data on steam plants. This is the data set used in the regression study by Wills (1978). Data for 1972–83 were added by my research assistants as new annual versions of the source volume were published by the Department of Energy. Starting in 1972, *all* new plants of vintage 1972 or later were included, as were current operating data for each year for pre-1972 plants already in the sample.

[10] The discrepancy between these average plant sizes and the average unit sizes cited earlier is accounted for by the fact that the average number of units in a new plant has ranged from 1.5 to 2.0 over the postwar years (with no noticeable trend).

Table 5.4 **Comparison of Output per Employee for Utility Industry and for Sample, 1948–82**

	Output per Employee (annual percentage growth rate)	
	Utility Industry	Sample
1948–52	8.6	6.9
1952–57	6.1	8.5
1957–62	5.8	5.5
1962–67	4.6	7.0
1967–72	3.8	4.0
1972–77	1.5	1.7
1977–82	–1.1	–1.0
Average growth rate	4.2	4.7

on short winter days). New plants had higher utilization rates than all plants during the 1952–62 interval but had substantially lower utilization rates from 1967 on. This phenomenon of relatively low utilization on new plants constructed in the late 1960s and 1970s may be indicative of unanticipated maintenance problems already alluded to above in connection with the rise and fall of supercritical units; it also may reflect the influence of environmental legislation, which makes some new plants more expensive to operate than their older brethren.

Row 3 exhibits the average number of employees per plant, and row 8 indicates the level of labor productivity, that is, output per employee. The universe of all plants shows rapid productivity growth through 1972, then a leveling off through 1983. An interesting comparison is provided by the growth in output per employee for the entire utility industry (including electric, gas, and sanitary) from row 2 of table 5.2, with the growth in output per employee for our sample of fossil-fuel steam generating plants, given in table 5.4.

The basic pattern of rapid growth followed by a leveling off and decline is observed for both series, but with differences. The deceleration of productivity growth for the entire industry is more gradual and for my sample of plants is more precipitous, with fairly steady and rapid growth through 1967, followed by a rapid slowdown and negative growth rate in the final half-decade interval at about the same rate as for the industry as a whole.

Rows 9 and 10 of table 5.3 display maintenance and fuel cost per unit of output. These both decline in nominal terms through 1967 and rapidly increase thereafter, reflecting both inflation and declining efficiency. Equivalent series are calculated in real terms in rows 12 and 13, where per-unit maintenance cost is deflated by the industry wage rate, and per-unit fuel cost is deflated by the price of coal.[11] This allows us to see more clearly

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[11] The industry wage rate and the price of coal are taken from table 5.2.

the "U-shaped" pattern of both real unit cost series, with the figures for all plants indicating a trough for real per-unit maintenance cost in 1967 and for real per-unit fuel cost in 1972. For new plants, the pre-1967 decline in real per-unit maintenance cost is less sharp, and the trough for real fuel cost is reached in 1967 rather than 1972.

Finally, row 11 exhibits equipment cost per unit of capacity. After increasing substantially between 1948 and 1952, this remains relatively constant for all plants until 1972, when a rapid increase begins. For new plants, the increase begins after 1967. When expressed as a ratio to the linked PPIs used by BEA in the PDE deflator, there is very rapid decline through 1967, followed by a modest increase.

The methodology developed in chapter 2 calls for the price change from an old model to a new model to be compared with their relative ability to generate net revenue at a fixed set of input and output prices. Since each electric plant is different, the concept of a "model" is not relevant, and I shall treat average figures for each successive "vintage" as if they represented successive models. The figures shown in rows 12 and 13 indicate an improvement in the efficiency of new plants in the usage of maintenance inputs and fuel until 1967 or 1972, and a deterioration after that. The methodology applied below translates this into a greater quality-adjusted decline in equipment prices before 1967 relative to the nominal equipment cost measure in row 11, but a greater increase after 1967.

5.5 Hedonic Price Regressions for Equipment Cost

The first step in the empirical analysis is to estimate hedonic price regression equations for the sample of new plants in which the dependent variable is the ratio of equipment price to capacity. All observations on new plants, as in table 5.3, refer to the year after the "vintage" (i.e., opening year) of the plant. Since the latest year of observation is 1983, the sample of new plants covers the vintages 1947–82. Because of relatively small sample sizes for each vintage, in which the mean values of equipment cost and quality attributes jump around substantially from vintage to vintage, the initial regression results reported in table 5.5 are based on a single equation estimated for the full sample period. The implicit prices (β_j) of j quality attributes (x_{ijt}) are constrained to remain the same over time, and price change is estimated by a string of time dummy variables (D_t):

$$(5.1) \qquad \log p_{it} = \beta_0 + \sum_{t=1}^{N} d_t D_t + \sum_{j=1}^{m} \beta_j x_{ijt} + u_{it} \, .$$

To test whether the β_j coefficients remained stable over the full set of vintages (1947–79), equation (5.1) is also estimated over shorter sample periods and is tested for structural change.

Table 5.5 **Hedonic Regression Equations Explaining the Log of Equipment Cost per Unit of Capacity All New Plants in Sample, Installation Years 1947–83**

	1947–79	1947–66		1966–79	
	(1)	(2)	(3)	(4)	(5)
1. Log capacity	−0.01	−0.15**	−0.20**	0.05	0.05
2. Log heat rate	0.61*	0.42	. . .	−0.01	. . .
3. Log number of units	−0.07	0.12*	0.16**	−0.15	−0.12
4. Fuel use:					
a. Coal only	0.17*	0.19**	0.16**	0.04	0.03
b. Oil only	−0.00	0.05	0.02	−0.24	−0.25
c. Gas only	−0.07	−0.13	−0.15*	−0.04	−0.05
5. Construction type					
a. Conventional	−0.05	−0.01	−0.02	−0.12	−0.11
b. Semioutdoor	−0.10	−0.04	−0.05	−0.25	−0.24
6. Vintage					
1949–50	0.02	0.04	0.04	. . .	. . .
1951–52	0.01	0.11	0.09	. . .	. . .
1953–54	0.16*	0.29**	0.27**	. . .	. . .
1955–56	0.10	0.31**	0.28**	. . .	. . .
1957–58	0.18	0.36**	0.33**	. . .	. . .
1959–60	0.29*	0.54**	0.51**	. . .	. . .
1961–62	0.26*	0.46**	0.42**	. . .	. . .
1963–64	0.08	0.35**	0.34**	. . .	. . .
1965–66	−0.08	0.24**	0.24*	. . .	. . .
1967–68	−0.04	. . .	. . .	−0.06	−0.06
1969–70	0.20	. . .	. . .	0.23*	0.22*
1971–72	0.33**	. . .	. . .	0.35**	0.36**
1973–74	0.54**	. . .	. . .	0.62**	0.62**
1975–76	0.76**	. . .	. . .	0.86**	0.85**
1977–78	0.73**	. . .	. . .	0.79**	0.79**
1979–80	1.47**	. . .	. . .	1.64**	1.65**
1981–82	1.61**	. . .	. . .	1.79**	1.79**
$\bar{R}^2$	.702	.625	.617	.736	.753
S.E.E.	.229	.153	.154	.270	.259
Observations	231	134	136	101	124

Note: All equations also include a constant and five location dummies, and two additional construction dummies.

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

Before turning to the results, a major limitation of the results should be recognized. This is a defect in common with previous hedonic regression studies of this industry and is not unique to this effort. With reference to section 3.4 of chapter 3, we have the "general excluded variable problem." The most important excluded variables are detailed specifications of the units composing each new plant, for example, pressure, temperature, type of coal used (high or low sulphur), and type of air and water pollution control equipment installed. The last omission is potentially serious and may lead us to interpret as price increases the substantial cost increases of generation equipment due to government-mandated pollution control equipment. To treat price indexes for this industry consistently with existing BLS price indexes for automobiles, which treat the cost of mandated pollution control and safety equipment as a quality change rather than a price change, the value of this equipment should be used to adjust the price changes implied by the hedonic coefficients.[12] The absence of variables in the data set for these types of equipment specifications will require us below to introduce rough ad hoc adjustments for this problem.

Fortunately, however, many of the other methodological problems with the hedonic methodology are not present here. For instance, the shifting relation between measured physical and unmeasured performance characteristics, which may have occurred for automobiles, is no problem for electric utilities, where the basic variables in the regression refer to performance, that is, the ability to generate a homogeneous unit of electricity. There is no problem of a shifting relation between list and transaction prices, since the data on the installed cost of equipment are obtained from buyers rather than sellers. Make effects are unlikely to be an important issue, since just two or three manufacturers dominate the industry, and in any case equipment makes are not identified in the data set. There is no "new product" problem, since we are measuring price change for the same product, which converts the same inputs into a homogeneous output, over the full postwar sample period. The only qualification is that factor inputs have not been homogeneous, due to the government-mandated replacement of high-sulphur by low-sulphur coal for some utilities, but this is another aspect of the more general "unobserved pollution control equipment" issue discussed above.

An issue that is of unique importance in the measurement of equipment prices for electric generation is the treatment of economies of scale. That is, if equipment price per unit of capacity declines with increasing average capacity per plant, should this be treated as a decline in the price index for equipment? This issue can be addressed if we write a simplified version of (5.1) in which there are only two vintages being observed, hence just one dummy variable, and a single quality characteristic, capacity (k_{it}):

$$(5.2)\qquad \log(p_{it}/k_{it}) = \beta_0 + \delta_1 D_1 + \beta_1 \log k_{it} + u_{it}, \quad t = 0, 1.$$

If the coefficient on capacity is significantly negative, then economies of scale are present and must be allocated between the manufacturer of equipment and increased market size. If there is an increase in the average capacity of each vintage, then measuring the price change between vintage 0 and vintage 1 as the coefficient on the vintage dummy (δ_1) amounts to attributing all the effect of economies of scale to increased market size. The alternative approach is to measure the change in the equipment price index

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[12] I defer to the conceptual chapters of the book the more general issue as to whether the BLS treatment of safety and antipollution devices as quality rather than price change is a desirable approach.

(P_t) as the coefficient on the dummy plus the effect of economies of scale in reducing equipment price per unit of capacity, thus crediting the full effect of economies of scale to the manufacturer:

$$\log P_1 - \log P_0 = \delta_1 + \beta_1(\log k_1 - \log k_0), \tag{5.3}$$

where β_1 is the coefficient on capacity in the regression equation (5.2), and k indicates the mean capacity of a given plant.

Since the role of scale economies has a substantial effect on the final price index that emerges from our calculations, some consideration of the proper treatment is appropriate. Reviewing the summary statistics in table 5.3, note that the issue is more important in the first half of the sample period, for the average capacity of new plants increased eight-fold in the interval between 1948 and 1967, but only by about 30 percent from 1967 to 1972, and virtually not at all after that. In the first published study of this industry based on the hedonic regression technique, Barzel (1964) attributed the full effect of economies of scale to the manufacturer, but without any substantive discussion. Ohta (1975) ignores the proper attribution of scale economies and thus implicitly assumes that equipment users consider a 100 percent increase in the capacity of a unit to represent less than a 100 percent increase in its quality. Wills (1978) also presents a price index based entirely on dummy variables for particular years without crediting the manufacturer for any of the effect of higher capacity in reducing equipment cost per unit of capacity.

One way to approach the issue is to ask why generator units were so small in the early part of the postwar period. Either manufacturers did not have the technical competence to produce larger units at reasonable cost, or markets were too small to support the purchase of larger units. If the first explanation is closer to the truth, the increase in scale over time was due to technological progress in the equipment producing industry, which reduced the cost of large units relative to small, and Barzel was right to adjust his price index for the scale effect. If market size rather than technical capability was the operative constraint, the approach taken by Ohta and Wills is correct.

One indirect piece of evidence that supports Barzel is that the average number of units installed per newly constructed plant during the early 1947–50 period was 2.0 rather than 1.0, and six plants in the data set were built with three or four units during that four-year interval. If larger pieces of equipment had been available at a lower cost per unit of capacity, they would have been purchased in place of two or more of the smaller units. This is even more true of boilers than generators, since early practice had been to install more than one boiler per generator.[13] It is universal in technical

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[13] Among the "major advances in the art" of steam-electric power generation in the early postwar years was "almost universal adoption of unit type construction—that is, a single boiler

descriptions of the industry's progress for the increased scale of units (and of plants, since the number of units per new plant did not change) to be attributed to technical progress. For instance, Cowing (1970, 39–40) writes that "the most important design advances contributing to this increased factor productivity have been significant increases in the feasible size of the turbine-generator units and the associated boiler, and in steam conditions. . . . This significant rate of technical change in steam-electric generation has been the result of significant advances in high-temperature metallurgy and in boiler and turbine design concepts." Similarly, Komiya (1962, 166), in his early path-breaking study, attributes increasing scale to the manufacturer: "The fact that it has become possible to build larger and larger generating units realizing the benefit of increasing returns is to be considered as the major achievement of technological progress in this industry." Indirect support of the view that size was constrained by technology comes from an engineering study (Kirchmayer et al. 1955, 613) carried out on units in the range of 50–100 KW: "we have every confidence that continued progress in metallurgy and design skill will make units larger than those now in operation economically feasible." One of their conference discussants stressed that "size must not run ahead of our proved progress in metallurgy. From recent evidence it seems that size has now outrun progress" (609).

The basic regression results are exhibited in table 5.5, where the functional form is assumed to be logarithmic (i.e., all variables other than dummy variables are entered as natural logs). The dependent variable is equipment cost per unit of capacity, and the explanatory variables are capacity, heat rate, and the number of units per plant. In addition, dummy variables are included for type of fuel used, type of construction, location in one of six regions of the country, and, corresponding to the D_t variables in (5.1) and (5.2), plant vintage. Because vintage dummies estimated for individual vintages tend to jump around owing to the small sample size, vintage dummies are included for pairs of years (e.g., 1949–50).

A notable feature of the results, as shown in column 1 of table 5.5, is an absence of price increase over the first two decades of the postwar period, as indicated by the coefficients on the vintage dummies, with a 29 percent increase from 1947–48 to 1959–60 more than offset by a 37 percent decline from 1959–60 to 1965–66. But then price increases began to be substantial, with an increase of 169 percent from 1965–66 to 1981–82 (these percentage changes are calculated as 100 times the change in the log). These price changes compare with increases in the linked PPIs used in the PDE deflator of 72 percent from 1947 to 1967 and 116 percent from 1967 to 1982.

The coefficients on the other variables contain some surprises. In contrast to an economies of scale parameter (β_1) of -0.185 found by Barzel (1964)

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for each turbine-generator—[which] has helped to reduce plant investment costs as well as annual operating costs" (U.S. Federal Power Commission 1969, ix).

for his early 1947–58 sample period, the scale parameter in column 1 is zero (−0.01). However, this single parameter disguises a shift in structure over the postwar years. Columns 2 and 4 display separate equations for the first and second parts of the postwar period, with the heat rate variable included, while columns 3 and 5 display separate equations with the heat rate variable excluded. When equations (with heat rate included) are estimated for the separate 1947–64 and 1965–82 subperiods, the $F(13,198)$ ratio for a change in structure in comparison with the full-period equation in column 1 is 2.40, which is significant at better than the 1 percent level.

Interestingly, this evidence of a change in structure occurs only when the regional location dummies are included. Without these variables, the F-ratio for the column 1 specification versus a break at 1965 falls well below the borderline for 5 percent significance. Yet the regional equipment cost differences are highly significant and widen substantially after 1965, perhaps indicating that environmental standards differed widely across regions. For instance, the regional location dummies indicate that, holding constant other attributes, equipment cost in the South was 28 percent less than in the Northeast before 1965, widening to 40 percent less after 1965. Even more radical was the difference between the Southwest (Texas, Oklahoma, etc.) and the Northeast, widening from 24 percent before 1965 to 69 percent after 1965.[14] These regional differences seem enormous, especially in light of the following table, which exhibits regional mean equipment cost per unit of capacity (in dollars per kilowatt), as well as the number of observations in each mean, for four subperiods:

Vintage	Northeast	North Central	South	Southwest
1947–55	123 (13)	131 (22)	100 (20)	96 (8)
1956–64	139 (17)	122 (10)	99 (13)	94 (4)
1965–71	111 (8)	122 (14)	89 (14)	77 (4)
1972–79	228 (8)	248 (20)	197 (14)	165 (12)

Between the first and last subperiod, there was no widening of the mean among the first three regions, while the mean increased in the Southwest by only 8 percent less (in logs) than in the Northeast. The discrepancy between the widening gap in the regional dummies, as contrasted with the absence of such widening in the regional means, may be explained by the shift in the fuel use dummies, which show a narrowing in the extra cost of coal compared to gas from 32 percent in 1947–64 to 7 percent in 1965–82. Thus, in the first period, the fuel dummies play more of a role in explaining the higher cost of equipment in the North, while, in the second period, the regional dummies provide more of the explanation.

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[14] All percentage changes in the text, as in table 5.5 to be discussed below, are calculated as changes in coefficients on dummy variables, i.e., changes in natural logs, multiplied by 100.

Previous investigators, especially Wills (1978), have devoted considerable attention to the distinction between ex ante and ex post substitution possibilities in the electric generating industry. While factor substitution is difficult and limited after a plant is built, it should be possible to substitute at the design stage, for example, to build a plant with a higher capital cost that uses less fuel. Thus, Joskow and Schmalensee (1983, 47) in their description of generation technology state that ''designers of steam-electric plants can increase fuel efficiency at the expense of capital cost.'' Evidence of this type of ex ante substitution would be found in a negative coefficient on the ''heat rate'' variable, indicating that a plant with a lower heat rate (i.e., lower fuel use per unit of output) has a higher equipment cost.

Thus, another surprising feature of the results in table 5.5 is the positive coefficient on the heat rate, and this coefficient is significant in the first column. Wills (1978, 503) reports the same finding of perverse coefficients on fuel efficiency and interprets this as the result of omitted attributes. Plants with expensive extra equipment (that is part of the dependent price variable but is not revealed by any of the independent variables) may use extra fuel, thus accounting for the positive coefficient on the heat rate variable in columns 1 and 2 of table 5.5. Because of this finding, Wills rejects all the ''many'' substitution models that he investigated and concludes that (ex ante) ''substitution possibilities are poor'' (503). While the heat rate variable is omitted by Wills in his final equipment price regression, table 5.5 exhibits equations for the two subperiods with and without this variable.

Wills's skepticism about the scope for ex ante substitution is also based on results in which labor input (employees per unit of capacity) is entered as an additional explanatory variable in the equipment cost regression. If firms can choose from a menu in which higher capital cost ''buys'' lower labor input, then one would expect a negative coefficient on the labor input variable. Wills finds, and my research confirms, that the coefficient on labor input is positive. When the log of the employment/capacity ratio is added to the equations in columns 2 and 4 of table 5.5, the respective coefficients (elasticities) are 0.09 and 0.14, respectively, both significant at the 10 percent (but not the 5 percent) level. It seems most plausible to regard the positive coefficients on both the heat rate and labor input as proxying for omitted quality attributes.

5.6 Price Indexes Implied by Hedonic Regression Equations

The price indexes implied by the regression coefficients of table 5.5 are summarized in table 5.6 and are compared there to the linked PPI series used in the PDE deflator and to indexes developed in other studies. All figures in the table are percentage changes (calculated as 100 times the log difference) over selected intervals, and the right-hand column shows the percentage change over the full period between the 1947–48 and the 1981–82 vintages. The linked PPI series is listed in row 1, with a full-period change of 186.8

Table 5.6 **Percentage Changes over Selected Intervals in Alternative Price Indexes for Steam-Electric Generating Equipment**

	1947–48 to 1957–58	1957–58 to 1965–66	1965–66 to 1971–72	1971–72 to 1981–82	1947–48 to 1981–82
1. NIPA engines and turbines	70.6	−7.9	30.0	94.1	186.8
2. Table 5.5 without capacity adjustment:					
a. Column 1	18.1	−26.4	40.6	128.4	160.7
b. Columns 2 and 4	35.7	−11.4	35.8	143.7	203.8
c. Columns 3 and 5 with heat rate omitted	32.6	−8.9	36.4	142.5	202.6
3. Table 5.5 with capacity adjustment:					
a. Column 1	16.7	−27.6	40.2	127.8	157.1
b. Columns 2 and 4	14.2	−28.8	37.6	146.8	169.8
c. Columns 3 and 5 with heat rate omitted	3.9	−32.1	38.2	145.6	155.6
4. Addendum: change in capacity (table 5.7)	143.4	115.8	36.9	61.5	358.7
5. Barzel	2.8	. . .	. . .	. . .	. . .
6. Wills	−7.5	−24.6	. . .	. . .	. . .

Sources by row: (**1**) See table 5.2 above, notes to row 6. (**2**, **3**, **4**) Regression coefficients underlying tables 5.5 and 5.7. (**5**) Barzel (1964, table 6, col. 1). (**6**) Wills (1978, fig. 4, p. 507). Wills used dummies for the average of three years. Figures reported in the 1947–48 column are his 1947–49, in the 1957–58 column are his 1956–58, and in the 1965–66 column are his 1965–67.

Note: All percentages are changes in logs multiplied by 100.

percent, as compared with the three indexes in row 2 calculated from the vintage dummy variable coefficients of table 5.5, with full-period changes ranging from 161 to 204 percent. The linked PPI series rose considerably faster than the hedonic indexes during the 1947–48 to 1965–66 subperiod and rose much more slowly between 1971–72 and 1981–82.

The next section of the table calculates changes in price indexes that adjust for the effect of changing capacity, as in equation (5.3). Rather than taking the arithmetic mean of capacity for these calculations, changes in capacity are taken from a regression equation for capacity, as shown in the first column of table 5.7. This "explains" the log of capacity by vintage and by the various dummy variables on fuel use, construction type, and region. Changes in capacity over successive vintages are shown by the vintage dummy variables in table 5.7 and are summarized in row 4 of table 5.6. Thus, the change in the price index shown in row 3 of table 5.6 is simply the change in the corresponding row and column of section 2 plus the change in capacity from row 4 times the coefficient on capacity from table 5.5.

There is no impact of the capacity adjustment with the specification of table 5.5, column 1, which holds constant the coefficient on capacity over the whole period and yields a zero coefficient. Larger adjustments occur in the other two specifications. The first of these, taken from columns 2 and 4 of table 5.5, estimates separate equations for the first and last part of the

Table 5.7 **Equations Explaining Fuel and Labor Input, All New Plants in Sample, Installation Years 1947–79**

	Log Capacity (1)	Log Heat Rate (BTU/kWh) (2)	Log Employees/ Capacity (3)
1. Log capacity	. . .	−0.08**	−0.73**
2. Log output	. . .	. . .	0.26**
3. Log number of units	1.18**	0.05**	−0.01
4. Fuel use:			
a. Coal only	0.37*	−0.03	0.27**
b. Oil only	−0.11	−0.05**	−0.08
c. Gas only	−0.00	−0.01	−0.09
5. Construction type:			
a. Conventional	−0.04	−0.01	0.05
b. Semioutdoor	−0.26	−0.01	−0.18*
6. Vintage:			
1949–50	0.24	−0.03	0.07
1951–52	1.04**	−0.06**	0.08
1953–54	1.24**	−0.09**	−0.21
1955–56	1.90**	−0.13**	−0.41*
1957–58	1.43**	−0.12**	−0.43**
1959–60	1.89**	−0.13**	−0.57**
1961–62	1.83**	−0.17**	−0.59**
1963–64	2.07**	−0.10**	−0.64**
1965–66	2.57**	−0.09**	−0.74**
1967–68	2.80**	−0.08*	−0.71**
1969–70	2.71**	−0.03	−0.67**
1971–72	2.98**	−0.03	−0.60**
1973–74	2.92**	0.00	−0.40*
1975–76	2.79**	0.01	−0.50*
1977–78	3.09**	0.04	−0.06
1979–80	2.91**	0.01	−0.48*
1981–82	3.59**	0.07	−0.53
$\bar{R}^2$	.756	.698	.808
S.E.E.	.592	.068	.371
Observations	268	229	268

Note: All equations also include a constant and five location dummies.

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

sample period (with an overlap in 1965–66). The second is identical but omits the heat rate variable, as in columns 3 and 5 of table 5.5. Because the shift in structure after 1965–66 involves a turnaround in the capacity coefficient from negative to positive, which is disguised by the zero coefficient in the full-period equation, the split equations yield larger estimated scale effects (−0.15 and −0.20, respectively) for the 1947–66 period when most of the capacity increase took place. During the 1947–66 interval, the three specifications summarized in row 3 of table 5.6 yield adjusted price declines of 10.9, 14.6, and 28.2 percent, respectively, a relatively narrow range, especially when compared with the NIPA increase of 62.7 percent. During the 1965–79 interval, the three specifications imply adjusted price increases of 169.0, 179.5, and 168.9 percent, all much greater than the NIPA increase of 124.1 percent.

Why is the lowest cumulative price increase over 1947–66 registered when the heat rate variable is excluded, as in row 3c? This occurs because the omission of the heat rate variable raises the scale effect in this period from −0.15 to −0.20, thus increasing the capacity adjustment made in the transition from row 2c to row 3c. Essentially, the specification that includes the heat rate, which appears with a positive coefficient, explains some of the decline in equipment price per unit of capacity before 1966 as stemming from the decline in the heat rate (i.e., improvement in fuel efficiency). When the heat rate variable is omitted, more of the explanation is "picked up" by the negative coefficient on capacity.

Previous research on price indexes for electric generating equipment has been carried out over shorter sample periods, precluding a full comparison with these results. A table in Barzel's (1964) paper allows a direct comparison with his results over the first decade of the postwar period, indicating that his scale-adjusted price change of just 2.8 percent is extremely close to the 3.9 percent in row 3c, which, like his approach, omits the heat rate variable. This similarity of results, despite several differences in the details of execution (including Barzel's omission of location dummies and technique of smoothing year-to-year equipment price changes by using the GNP deflator as an interpolator), reflects in part an extremely close estimate of the scale effect (−0.185 for Barzel and −0.20 in table 5.5, col. 3). In Wills's (1978) results, summarized in row 6 of table 5.6, the estimated price decline is greater than in any of my results for the first decade, but less than my scale-adjusted results in the second decade. Differences are due to Wills's use of a linear rather than a logarithmic specification and of an instrumental variable technique, as well as his omission of location dummies.[15]

5.7 Adjusting for Changes in Operating Cost

The technique of price measurement proposed in chapter 2 centers around the concept of "net revenue," defined as gross revenue minus operating costs, that is, the amount available for depreciation, interest, and before-tax profits. As applied in the analysis of chapter 4 on commercial aircraft, price differences between old and new models of a given product are adjusted for changes in net revenue yielded by new models. Holding constant the price of a model that remains unchanged, a quality adjustment is made if the ratio of net revenue generated by the new model relative to the old model does not

[15] Wills (1978, table 2, p. 506) presents an alternative set of results with random coefficients estimation that exhibits virtually no price decline between 1947–49 and 1965–67.

equal their ratio of sales prices. To repeat equation (2.35) from chapter 2, the change in the real input price index (dp/p) that holds constant the cost of producing identical models is

$$dp/p = [v_1 n_0]/[v_0 n_1] - 1, \tag{5.4}$$

where v designates the purchase price of models 1 and 0, and n designates their respective net revenue.[16] For the purpose of the calculations in this chapter, it is convenient to express (5.4) in logs:

$$d \log p = d \log v - d \log n. \tag{5.5}$$

Expressions (5.4) and (5.5) both state that the "real" price change will be zero if both purchase price (v) and net revenue (n) change in proportion between model 0 and model 1. The nominal price index P is then obtained by adding the change in the real input price from (5.4) to the change in the price index for identical models (C). Copying (2.36) and converting to logs, we have:

$$d \log P = d \log p + d \log C. \tag{5.6}$$

The task of this section is to compute a time series on net revenue for my sample of generating plants to be inserted into (5.5) and (5.6). In contrast to my study of commercial aircraft, where data on discrete "models" are available, the data set on electric generating plants contains no such model identification, and in fact each boiler-generator unit is unique. An obvious alternative is to treat each "vintage" of electric generating plants as a "model" for the purpose of computing the components of (5.5) and (5.6). Because the size and average equipment cost of plants tend to jump erratically from year to year, we compute the net revenue and equipment cost ratios needed in (5.4) for *pairs* of vintages (e.g., 1947–48, 1949–50, etc.). This is the same procedure already followed in the hedonic regression equations presented in table 5.5 above.

In the aircraft study, the change in the price of identical models (C) could be measured directly. For electric generating equipment, where there is no "model" concept, I choose instead to identify the price of a constant-quality model with the coefficients on the vintage dummies in the hedonic regression equations of table 5.5. Then the comparison of net revenue and sales price ratios, required in (5.4) for the computation of the change in the "real" price index, is based on changes in net revenue per unit of capacity and in equipment cost per unit of capacity between one vintage pair (say 1947–48) and the next vintage pair (say 1949–50), holding constant input and output prices at the values of 1947–48.

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[16] The "curvature adjustment" included in the analysis of chap. 2 is omitted here to simplify the discussion.

The change in the real equipment price ($d \log v$) is taken from the hedonic regression equations of table 5.5. Since the price changes captured by the vintage dummies are already included in the constant-quality price index ($d \log C$), the remaining "real" price change per unit of capacity is computed as the coefficient on capacity (β) times the change in capacity ($d \log k$):

$$d \log v = \beta \, d \log k. \tag{5.7}$$

For this calculation, the β coefficients are taken from the split regression that excludes the heat rate variable, that is, columns 3 and 5 of table 5.5, and the sum of the two change components ($d \log C$ and $d \log v$) corresponds exactly to the change summarized in table 5.6, row 3c.

Since an electric utility earns revenue from the joint activities of generation, transmission, distribution, and bill collection, no figure is recorded for the gross or net revenue of a generating plant. However, as in the case of commercial aircraft, it is possible to prorate revenue among the different cost categories if we assume that the same operating margin is earned in each category. In 1983, for instance, the electric utility industry earned net revenue equal to 40.7 percent of operating cost, calculated as follows (all figures are billions of dollars):[17]

Gross revenue	$ 117.3
Less taxes included in operating expense	− 17.4
Equals available revenue	99.9
Less operating expense	71.0
Equals net revenue (depreciation, amortization, and net operating income)	28.9

Thus, net revenue/operating expense = 28.9/71.0 = .407.

Letting z stand for the ratio of net revenue to operating expense, and assuming that the industry ratio (e.g., .407) also applies to each generating plant, the net revenue of a plant can be computed from its operating expense (x):

$$n = (1 + z)(x) - x = zx. \tag{5.8}$$

We want to measure the change in net revenue that occurs when, holding gross revenue constant, a change in fuel or labor requirements creates a change in operating cost. This is simply[18]

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[17] The source is U.S. Department of Energy (1984, table 3, p. 11).

[18] Again denoting an initial and subsequent situation with subscripts 0 and 1, we have the change in net revenue, caused by a change in input requirements when gross revenue is held constant, as:

$$\frac{n_1 - n_0}{n_0} = \frac{-dx}{n_0} = \frac{-dx}{zx_0}.$$

$$d \log n = -(1/z)d \log x. \tag{5.9}$$

The last step is to define operating cost (x) as the sum of fuel and labor maintenance cost. Fuel cost in turn is equal to the price of fuel (p^f) plus fuel requirements measured in BTU per kWh (f). Labor maintenance cost is equal to the price of maintenance labor per employee (p^e) plus labor requirements measured in employees per kWh (e):

$$x = p^f f + p^e e, \tag{5.10}$$

and the change in operating cost at fixed input prices is

$$d \log x = \alpha d \log f + (1 - \alpha)d \log e, \tag{5.11}$$

where α is the share of nominal fuel expense in total operating expense. Combining (5.9) and (5.11), the change in net revenue is

$$d \log n = -(1/z)[\alpha d \log f + (1 - \alpha)d \log e]. \tag{5.12}$$

Finally, the change in the real price index is, from (5.5) and (5.7) above, is

$$d \log p = \beta d \log k + (1/z)[\alpha d \log f + (1 - \alpha)d \log e]. \tag{5.13}$$

This equation identifies three sources of a reduction in the real price index (p), the reduction in price per unit of capacity associated with an increase in capacity, the benefit of which is credited to the manufacturer, to a reduction in fuel requirements per unit of output, and to a reduction in labor requirements per unit of output. All three of these factors were important sources of reductions in the real price index prior to the late 1960s, but not since then.

To calculate the change in net revenue in (5.12), we need only the share of fuel expense in total operating expense (α) and changes in fuel and labor input requirements per unit of output. The α weights are taken from the means for new plants in the data set of nominal fuel and maintenance labor expense for each vintage pair. The latter ($d \log f$ and $d \log e$) are taken from the regression equations of table 5.7, where heat rate and the employee/capacity ratio are explained by the same set of variables that appear in my hedonic regression equations for equipment cost. The negative coefficients on capacity indicate substantial scale effects for fuel use and especially for labor. An improvement in fuel efficiency occurred between the 1947–48 and the 1961–62 vintage pairs, followed by a steady deterioration through the end of the sample period. Labor efficiency improved through 1969–70 and deteriorated thereafter. Holding capacity constant, fuel efficiency was slightly worse in 1981–82 than in 1947–48, while labor efficiency was 53 percent better.

Just as we attribute the scale effects in the price equation to the manufacturer, those in the fuel and labor efficiency equations are also treated in the same way. Thus, the change in efficiency between two vintage pairs is

Table 5.8 **Components of Operating Cost Adjustment**

Year Pair	$d \log v$ $= \beta\, d \log k$ (1)	α (2)	$d \log f$ (3)	$d \log e$ (4)	$d \log n$ (5)	$d \log p^i$ (6)
1947–48		94.0				
1949–50	−4.8	94.4	−4.9	−10.5	−12.8	−17.6
1951–52	−16.0	94.7	−9.4	−57.4	−29.3	−45.3
1953–54	−4.0	93.1	−4.6	43.6	−3.1	−7.2
1955–56	−13.2	94.4	−9.3	−68.2	−31.0	−44.2
1957–58	9.4	94.1	4.8	32.3	15.8	25.2
1959–60	−9.2	90.7	−5.5	−47.6	−23.1	−32.1
1961–62	1.2	93.0	−3.5	2.4	−7.6	−6.4
1963–64	−4.8	91.4	4.9	−22.5	6.2	1.4
1965–66	−10.0	92.9	−3.0	−46.5	−15.0	−25.0
1967–68	1.2	89.0	−0.8	−13.8	−5.5	−4.3
1969–70	−0.5	89.0	5.7	10.6	15.3	14.8
1971–72	1.4	88.4	−2.2	−12.7	−8.4	−7.0
1973–74	−0.3	91.5	3.5	24.4	13.0	12.7
1975–76	−0.7	92.7	2.4	−0.5	5.4	4.7
1977–78	1.5	90.2	0.6	−20.9	−3.7	−2.2
1979–80	−0.9	88.5	−1.6	14.1	0.5	−0.4
1981–82	3.4	91.7	0.6	−54.6	−9.8	−6.4
Sum of log change	−46.3		−22.3	−227.8	−93.1	−139.4

Sources by column: **(1)** Change in time coefficients in capacity equation from table 5.7, col. 1, times coefficient on capacity in table 5.5, col. 3, until 1965–66, and col. 5 thereafter. **(2)** Share of fuel cost in sum of fuel and maintenance cost, from sample means for new plants. **(3)** Change in time coefficients in heat rate equation from table 5.7, col. 2, plus change in time coefficients in capacity equation from table 5.7, col. 1, times coefficient on capacity in table 5.7, col. 2. **(4)** Change in time coefficients in employment equation from table 5.7, col. 3, plus change in time coefficients in capacity equation from table 5.7, col. 1, times coefficient on capacity in table 5.7, col. 3. **(5)** The fraction $1/z$, where $z = .407$, times the weighted average of cols. 3 and 4, using col. 2 as weights. **(6)** Column 1 plus col. 5.

the coefficient on the vintage dummy in the fuel and labor requirement equations of table 5.7, plus the coefficient on capacity times the change in capacity (where the change in capacity in each vintage pair is taken from the regression coefficients in the first column of table 5.7). Because I have no data on the effect of environmental regulations on operating efficiency or on equipment cost, my approach lumps together the effects of technological improvements achieved by the manufacturer with retrogression caused by environmental regulations; I deal separately with this problem below.

The calculations are carried out in table 5.8. The first column lists the price change associated with the direct effect of changing capacity on price ($\beta d \log k$); this is identical to the capacity effect taken into account in the middle of table 5.6. Column 2 lists the weight of fuel cost in total operating cost; this remains over time in a relatively narrow range of 88–95 percent and is lower on average in the last half of the sample period. The changes in fuel and labor requirements are reported in columns 3 and 4, where the numbers shown combine the direct changes measured by the time dummy coefficients listed in table 5.7 with the scale adjustment. A negative entry indicates improved efficiency, and a positive number indicates deteriorating

Table 5.9 **Alternate Price Indexes for Electric Generating Equipment, 1947–82 (1971–72 = 100)**

	Linked PPIs used to Deflate PDE (1)	Hedonic with Capacity Adjustments (2)	Hedonic with Capacity and Operating Expense Adjustments (3)	Same as (3) with 1973–78 Adjustment for Environmental Regulation (4)
1947–48	40.7	117.7	315.2	315.2
1949–50	42.2	114.5	269.7	269.7
1951–52	47.4	104.6	183.9	183.9
1953–54	52.0	107.8	183.7	183.7
1955–56	60.0	89.0	111.2	111.2
1957–58	80.4	105.9	155.0	155.0
1959–60	82.1	107.8	125.2	125.2
1961–62	72.7	105.9	114.0	114.0
1963–64	72.6	84.3	96.6	96.6
1965–66	74.3	65.0	64.1	64.1
1967–68	81.6	68.5	63.9	63.9
1969–70	93.2	86.6	94.2	94.2
1971–72	100.0	100.0	100.0	100.0
1973–74	109.6	123.0	140.1	133.4
1975–76	152.7	152.2	182.9	166.2
1977–78	177.7	149.9	173.7	150.1
1979–80	209.1	281.8	328.1	266.7
1981–82	248.7	335.3	354.0	274.3

Sources: Column 1 from table 5.2, row 6. Column 2 calculated from table 5.5, cols. 3 and 5. Column 3 calculated from tables 5.5 and 5.8. Column 4 adjustment as described in text.

efficiency. Negative entries predominate until 1967–68, and positive entries thereafter. Finally, the two right-hand columns exhibit the change in net revenue (n) calculated with equation (5.12) and the change in the real price index (p) calculated with (5.13). The cumulative improvement in fuel efficiency is 31.3 percent through 1967–68, followed by a 9.0 percent decline thereafter. For labor, the improvement through 1967–68 is 188.2 percent, followed by a further but smaller improvement of 39.6 percent. For the real price index shown in the final column, the cumulative real price change through 1967–68 is 155.6 percent, followed by an increase of 16.2 percent from then until 1981–82.

The end result of these computations is displayed in columns 2 and 3 of table 5.9. The table begins in column 1 with the linked PPIs used in the NIPA to deflate PDE in steam turbine generators. In the second column is the index, corresponding to table 5.6, row 3c, based on the hedonic price equations with an adjustment for the capacity scale effect, but with no treatment of changes in operating efficiency. The third column contains the nominal price index with the full set of operating efficiency adjustments. The change between vintage pairs of this index is computed from equation (5.6), where the change in the price of a constant-quality unit, $d \log C$ (taken as the change in the vintage dummy coefficients in cols. 3 and 5 of table 5.5), is added to the change in the ''real'' price index ($d \log p$) from the right-hand column in table 5.8.

5.8 The Impact of Environmental Legislation

The price indexes in table 5.9 show a consistent pattern. Both of the new indexes decline relative to the NIPA index before 1971–72 and exhibit a relative rise thereafter. Because both fuel and labor efficiency per unit of capacity improved prior to the late 1960s and deteriorated thereafter, the final index that incorporates the operating efficiency adjustments declines relative to the other two indexes before the late 1960s and increases thereafter. Using either of the two new indexes as a deflator for investment spending in the national accounts would lead to the conclusion that the growth rate of real investment in the NIPA is drastically understated before the late 1960s and overstated thereafter.

However, we have not yet taken into account the effects of environmental legislation, which probably has a greater impact on the electric utility industry than on any other, with the possible exception of automobiles and steel. Since World War II, most coal has been burned in pulverized form in furnaces at sufficiently high temperatures to produce not only the steam that drives the turbines, but also nitrogen and sulfur oxides, both linked to acid rain. The 1970 Clean Air Act contained amendments that divided responsibility for control of emissions from electric utility generating stations. States were given responsibility for designing standards for plants built before August 1971, while new plants built (or old plants substantially modified) after that date were subject to explicit quantitative emissions controls (measured in pounds of sulfur dioxide per million BTUs of fuel input). Under 1977 amendments, new plants are required to install an emissions desulfurization system, usually called ''scrubbers.''[19]

In the national accounts, price changes due to environmental legislation are omitted in the calculation of real investment in consumer and producers' durables. That is, a catalytic converter added to an automobile is treated as an improvement in the quality of the automobile, even if the consumer would not purchase the device freely, on the assumption that society as a whole receives benefits from such devices in an amount roughly equal to their cost. To treat electric utility equipment symmetrically with automobiles, those price increases in generating equipment attributable to environmental legislation must be omitted from the price indexes developed here.

The impact of environmental legislation on quality-adjusted price indexes for electric utility generating equipment takes two main forms. First, there is

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[19] Details of environmental legislation and regulations can be found in Gollop and Roberts (1983).

the direct expense incurred in purchasing pollution control equipment, which primarily consists of scrubbers. If possible, we should subtract from the price increases in table 5.9 those attributable to the added cost of scrubbers and similar equipment. Second, environmental legislation can impair both fuel and labor efficiency, by requiring the use of nonpolluting types of fuel that require more BTUs to generate a unit of electricity and by requiring additional maintenance labor to service the scrubbers and other pollution-control equipment and to remove the wet sludge that collects in the scrubbers as part of the mechanical process by which they remove pollutants. To correct for this effect, we should adjust changes in fuel and labor requirements previously used to develop fuel and energy efficiency adjustments for the estimated impact of environmental legislation. A third effect of environmental legislation, the addition of high cooling towers to reduce pollution, has the same economic effects as scrubbers but is included in the cost of the plant structure, not in the separate total for plant equipment, which concerns us in this chapter.

There is substantial evidence and even more hearsay regarding the direct increase in the price of equipment attributable to scrubbers and other mandated equipment. The best academic evidence is that of Joskow and Rose (1985), who provide econometric estimates explaining total plant construction cost, using a data set that contains specific technical variables not available in my data. Their estimates of the coefficient on a scrubber dummy variable average out to 0.15, that is, scrubbers have added an estimated 15 percent to the construction cost of coal-fired plants. Joskow and Rose stress that this estimate does not include the capital costs of all environmental control equipment, for which they cite (1985, 20) an industry source as indicating a 20–30 percent addition to the cost of a typical unit. In a totally different ballpark is an estimate that refers to all government-mandated equipment; a 1979 study by Ebasco Services estimated that fully 62 percent of the cost of a new coal-burning plant in that year was attributable to the cost increase "from statutory and regulatory changes" (quoted in Faltermayer 1979, 118). Bain (1986) cites a figure of one-third of the cost of building a power plant. Prewitt (1988) estimates a cost of 14–20 percent.[20]

On maintenance requirements, one source estimates that scrubbers require as much maintenance as the rest of the plant taken together.[21] In earlier research (Gordon 1985), I conducted telephone interviews with plant managers to investigate sources of the productivity slowdown in the electric generating industry and the existence of "left-out variables" that could

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[20] The cost of add-on scrubbers is stated to be $200–$300 per kilowatt of capacity as compared with a total estimated plant cost of $1,500 "required to build a new coal-burning plant from scratch" (Prewitt 1988, 180).

[21] The source is Weaver (1975), who cites the Cholla plant in Arizona, the first to have a "working" scrubber, as requiring a 50 percent increase in its maintenance labor force.

affect the results of econometric equations explaining employment (like that presented in table 5.7, col. 3). I found that no plant manager cited work force additions connected with pollution control equipment exceeding 25 percent. The conflict between this finding and the other evidence cited above is that my survey was conducted over a sample of existing plants, not necessarily newly constructed. Recall that the environmental regulations call for scrubbers on new plants after 1977, but not necessarily on earlier plants. Only one of the plants in my survey was equipped with a scrubber, and its manager stated that fully 25 percent of the plant work force was required for the operation and maintenance of the scrubber; other plants in the survey were equipped with electrostatic precipitators, which appear to have much less onerous maintenance requirements.

Overall, it would appear that 20 percent would be a conservative estimate for the early 1980s of the fraction of equipment cost in new plants consisting of environmentally mandated devices, including not only scrubbers but all other equipment designed to reduce both air and water pollution. If we assume that plant scale has not been affected by legislation, then we can simply subtract 20 percent from the estimated time dummy coefficients in the equipment cost regression of table 5.5 in the most recent year covered, 1981–82, and interpolate that adjustment linearly back to 1971–72, the time when the legislation first went into effect. As for maintenance labor, 20 percent is subtracted from the 1981–82 labor requirement used in the calculation of net revenue in table 5.8. In the absence of any specific quantitative evidence, no adjustment is made for any effect of environmental regulations on fuel efficiency, which, in view of the widespread shift to less efficient fuel, makes it likely that the overall adjustment is too conservative.

The "environmentally adjusted index" is shown in column 4 of table 5.9. The adjustment begins in the 1973–74 year pair and becomes larger until, in 1981–82, the resulting adjusted index number is 77.4 percent of the unadjusted index number. Almost all the adjustment is due to the direct vintage coefficient in the price equation of table 5.5, that is, the cost of the equipment itself, and relatively little to the additional adjustment for changes in labor efficiency. Before adjustment, the 1972–82 annual growth rate of the new index, 12.6 percent, greatly exceeded the 9.1 rate registered by the PPI, but, after adjustment, the rate of 10.1 percent is substantially closer to that of the PPI. Since there are few examples in this book of new price indexes that rise substantially faster than the PPI over any period, the more moderate inflation registered by the adjusted new index has a certain plausibility.

5.9 Conclusion and Topics for Further Research

There are a number of questions that could be addressed in future extensions of this research. First, the statement of net revenue per unit of

Table 5.10 **Equation Explaining Log Utilization Rate, All Plants in Sample, Years of Operation 1948–80**

1. Log capacity	0.01
2. Log heat rate	−1.24**
3. Log number of units	−0.06**
4. Fuel use:	
a. Coal only	0.18**
b. Oil only	−0.08**
c. Gas only	−0.03
5. Construction type:	
a. Conventional	−0.03*
b. Semioutdoor	0.05*

6. Vintage and time:	Vintage	Time
1949–50	0.08**	−0.20**
1951–52	0.10**	−0.20**
1953–54	0.10**	−0.29**
1955–56	0.10**	−0.42**
1957–58	0.19**	−0.54**
1959–60	0.12**	−0.68**
1961–62	0.16**	−0.72**
1963–64	0.19**	−0.67**
1965–66	0.15**	−0.62**
1967–68	0.16**	−0.62**
1969–70	0.06	−0.61**
1971–72	0.06	−0.59**
1973–74	−0.01	−0.60**
1975–76	−0.04	−0.85**
1977–78	0.06	−0.79**
1979–80	−0.02	−0.86**
1981–82 (1983)	−1.35**,[a]	−0.89**
$\bar{R}^2$	0.344	
S.E.E.	0.458	
Observations	6,479	

*Indicates significance at the 5 percent level.

**Indicates significance at the 1 percent level.

[a] No new plants in sample for 1983.

capacity in (5.12) assumes no change in utilization, since fuel expense per unit of capacity is defined as heat rate times fuel cost per BTU times output per unit of capacity. However, over the postwar period, there have been significant changes in the utilization rates of different vintages, observed over their lifetimes. A regression equation (shown in table 5.10) for all plants in the sample, that is, each vintage is observed from the year after its installation to 1983, shows an improvement in average utilization, holding year of operation constant, over vintages from 1947–48 to 1965–66, followed by a marked deterioration. If this change in utilization by vintage is attributed to the manufacturer, because technical change can make a new vintage more efficient and therefore more attractive for base-load capacity, then the adjustment for fuel efficiency in (5.7) would be calculated as the existing heat rate change, plus the effect of capacity on heat rate, plus the vintage and capacity effects on utilization. Any such additional adjustment would simply accentuate the differences evident in table 5.9, with a greater decline in the index shown in the third column through the mid-1960s, and a greater relative increase thereafter. However, this conclusion would be premature, pending an investigation of the effects of seasonality and other market demand factors on utilization. For instance, reduced utilization may be primarily due to an increased dispersion of summer and winter peak loads as the use of air conditioning has spread.

Second, the net revenue adjustments are based on the experience of operating a new plant only in the first year after its installation. Firms might, however, make a calculation that takes into account different expectations about the future time path of fuel and labor prices. For instance, if wage rates were expected to increase relative to fuel prices during the first two decades of the postwar period, then the present value of future maintenance expense would be a greater share of the present value of total future operating expenses than indicated by the share of maintenance in the first year of operation. Since the labor efficiency adjustments in table 5.8 are greater in percentage terms than the fuel efficiency adjustments, placing a greater weight on labor cost would add to the overall size of the adjustments and further accentuate the differences of the final operating-cost-adjusted price index in comparison with the other indexes before and after 1970.

While there is much to be done, one conclusion emerges clearly in this chapter. Over the first half of the postwar era, few, if any, products exhibit a greater difference between the fully adjusted alternative price index (table 5.9, col. 4) and the equivalent PPI. The drift over 1947–48 through 1967–68 amounts to a staggering −11.5 percent per year. In the official BLS breakdown of productivity growth, the electric utility industry exhibits rapid growth in the early postwar years, followed by a steady slowdown, to virtual stagnation since 1973. This chapter demonstrates that this history cannot be blamed on any aspect of behavior by employees or managers within the utility industry itself. Instead, credit for the early achievements and blame for the subsequent failures should be directed toward the manufacturing sector, both the companies making generators and boilers, and those in other companies and industries responsible for the advances in metallurgy that ultimately made possible much of the increase in scale of equipment and the accompanying decline in price per unit of capacity.