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Vintage-Level Energy and Environmental Performance of Manufacturing Establishments

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VINTAGE-LEVEL ENERGY AND ENVIRONMENTAL PERFORMANCE OF MANUFACTURING ESTABLISHMENTS

G.A. Boyd, M.J. Bock, M.J. Neifer, and M.H. Ross

STRACT

This report examines the relationship between an industrial plant's vintage and its energy and environmental performance. Basic questions related to defining vintage and measuring the effects of the manufacturing industry's vintage distribution of plant-level capacity and energy intensity are explored in general for six energy-intensive sectors (paper, chlorine, nitrogenous fertilizer, aluminum, steel, and cement) at the four-digit standard industrial classification (SIC) level and in detail for two sectors (steel and cement). Proprietary plant-level data used in this project came from U.S. Bureau of the Census surveys and external sources such as trade associations. Access to the Bureau's data was provided through its Center for Economic Studies. Results show that greenfield (i.e., newly opened) plants in the paper, steel, and cement industries exhibit low fossil fuel intensities. These results are consistent with expectations. New plants in the paper and steel industries, where processes are undergoing electrification, exhibit high electricity intensities. When a vintage measure is assigned to plants on the basis of trade association data, significant declines in fossil fuel intensities attributable to vintage are found in the steel and cement industries. However, no systematic differences in the level of utilization of different vintages are found. An analysis of a subsector of the steel industry — minimills that use scrap-based, electric arc furnaces — reveals a decline in electricity intensity of 6.2 kilowatt-hours per ton for each newer year of installed vintage. This estimate is consistent with those of engineering studies and raises confidence that analyses of vintage effects in other industries could be conducted. When a vintage measure is assigned on the basis of investment data rather than trade association data, the vintage/performance relationship results for the cement industry are reasonably robust; thus, the analysis of vintage and performance could be extended to sectors for which only U.S. Bureau of the Census data are available.

SUMMARY

This report examines the relationship between an industrial plant's vintage and its energy and environmental performance. It explores basic questions for selected energy-intensive industrial sectors at the four-digit standard industrial classification (SIC) level:

- How can vintage be defined and measured?
- What are energy intensities and pollution-abatement costs at the plant level for different vintages?
- How does the manufacturing industry's vintage distribution affect its aggregate energy use?

The answers to these questions are formulated on the basis of actual observations of plant-level operations, not engineering estimates.

The plant-level data employed for this project come from surveys conducted by the U.S. Bureau of the Census (Bureau). The Bureau uses the data from these surveys to construct industrywide and economywide aggregate figures on manufacturing activity for release to the public in a variety of reports. The Bureau's Center for Economic Studies (CES), through its program of Census Fellows and Special Sworn Employees (SSEs), gives the public access to the underlying data. The Bureau established the CES to encourage research on economic and modeling issues that involve plant-level data. However, all results of any analyses conducted at the CES are reviewed to ensure they do not disclose any confidential plant-level information.

This report first examines greenfield (i.e., entirely new) plants in six of the most energy intensive industries at the four-digit SIC level. In general terms, they are steel mills, pulp and paper mills, and the chlorine, nitrogenous fertilizer, cement, and primary aluminum industries. New plants are compared with the industry average in terms of energy and environmental performance. Energy performance is measured by energy (electricity or fossil fuel) intensity (i.e., the energy/output ratio). Since the Bureau's environmental databases are not yet complete, environmental performance is measured by a proxy — energy use. For carbon dioxide and many other pollutants, energy use is a good proxy.

For the paper, cement, and steel industries, results are consistent with expectations. For new plants in these industries, fossil fuel intensities are lower. For new plants in the paper and steel industries, in which processes are undergoing electrification, electricity intensities are higher. However, new plants in all six industries represent only a small percentage of the total plants covered by the data, so a more detailed analysis is conducted here.

This report focuses on the steel and cement industries. They were selected because data on the installation dates of major equipment (i.e., steel furnaces and cement kilns) are

available from external, nongovernmental sources for these two industries. Vintage is assigned on the basis of these external data, and a series of analyses is performed. The analyses involve the use of an accounting framework to measure the contribution of:

1. Energy intensity for each vintage;
2. Utilization of each vintage (i.e., the fraction of production capacity that is used); and
3. Share of capacity or capital stock represented by each vintage.

The computation of vintage shares (item 3) is relatively straightforward. From data on shares, researchers can determine how much capacity is older than some target age (e.g., 30 years or more) or how much capacity is above some target level of energy intensity. Even more interesting conclusions emerge from the analysis of vintage utilization (item 2) and vintage energy intensity (item 1).

In the analysis of utilization of plants by vintage class, no remarkable patterns are exhibited. The expected result — low utilization of older vintage plants and high utilization of newer vintage plants — is not seen in the data, suggesting that utilization is a much more complex concept than a simple "use the newest first" rule would imply.

Vintage plays a significant role in affecting a plant's fossil fuel intensity in both the steel and cement industries; newer plants have lower fossil fuel intensities. However, vintage does not explain a large part of the plant-level variation found in these industries. For cement manufacturing, there is a decline of 1-3% (depending on how energy intensity is defined) in fossil fuel intensity per year of vintage. For steel, the decline is 1.3-3% per year. The results on electricity intensity in cement manufacturing are not statistically significant. The results on electricity intensity in the steel industry are obscured by important structural changes that took place in that sector. As a result, a more focused examination of the electricity-intensive segment of this industry — the minimill sector — is undertaken.

The growth of the segment that employs minimills using scrap-based, electric arc furnaces has been responsible for the rising average electricity intensity of the steel industry. However, engineering studies suggest that the technology being used in this segment has improved in terms of its energy use. When the most efficient minimills in the sample are identified, a statistical model that controls for plant-level utilization estimates that there is a decline in energy use of 6.2 kilowatt-hours per ton of steel per year of vintage (i.e., as plants become newer). This result closely agrees with engineering estimates, a fact that assures researchers that valid estimates of vintage-based trends can be extracted from plant-level data in other sectors as well.

An analysis of alternative measures of vintage (in which the Bureau's investment data are used for the cement sector) suggests that the quantitative results are relatively robust. Although it would be preferable to extend these results with more external data

(e.g., from the American Paper Institute or some other trade association), it is possible to estimate the effect of vintage by using the plant-level data available from the Bureau.

The data developed in this study can be used for a variety of policy analyses. For example, one type of information from the Longitudinal Research Database (LRD) maintained at the Bureau — when combined with trade association data — that is relevant to research and development needs is the historical rate at which capacity has been created at new facilities. In Figure S.1, the fraction of total capacity built within any specified time is shown for the cement and steel industries. (Here age is defined as the difference between the observation year, 1987, and the date of the last major facility change, that is, its vintage). Figure S.1 shows that if capacity additions and retirements continue to occur at the same rate as they have in the recent past, in 5 years after the base year (the year when new process technology becomes available), almost 20% of capacity in these industries will be at plants with major equipment installed after that base year. After 10 years, one-third of the capacity will be at such new plants.

Figure S.2 illustrates a conclusion that can be reached by examining capacity and energy intensity distributions by vintage. The plot shows the decline in average energy intensity (fossil fuel use per unit of capacity) that would occur in the cement and steel industries if the oldest capacity were retired and replaced with capacity exhibiting the energy intensity of the newest vintage. For the cement industry, the first large gain occurs after the first 20-25% of capacity is replaced. This gain represents replacement of plants 25 years of age or older (see Figure S.1). Thereafter, the improvement is roughly linear. For the steel industry, the results appear to be more dramatic, but they should be carefully interpreted. Dramatic improvement occurs as the oldest half of the industry is replaced; gains are modest thereafter. However, the newest plants are virtually all scrap-based minimills, which cannot produce the same steel products as the older ore-based and coke-based mills. If the transition shown in Figure S.2 were to occur, the quality of scrap-based steel would have to improve dramatically or higher-quality steels would have to be imported.

FIGURE S.1 Share of Production Capacity of Plants Younger Than a Given Age in 1987 for the Cement and Steel Industries

FIGURE S.2 Impact of Retirement of Old Capacity on Fossil Fuel per Unit of Capacity for the Cement and Steel Industries

1 INTRODUCTION

This report examines the relationship between an industrial plant's vintage and its performance with respect to energy and the environment.¹ It explores basic questions for selected energy-intensive industrial sectors at the four-digit standard industrial classification (SIC) level:

- How can plant vintage be defined and measured?
- What are energy intensities and pollution-abatement costs for different plant vintages?
- How does the distribution of plant-level capacity and energy intensity by plant vintage affect an industry's aggregate energy use?

These questions are addressed on the basis of an analysis of plant-level operations, not engineering estimates.

Other factors being equal, one might expect older plants to be less energy efficient and to pollute more. Older manufacturing plants would thus be a potential source for reducing energy demand and mitigating environmental effects. By the same token, certain policies like carbon taxes and other environmental regulations could adversely affect the manufacturing sector by forcing older plants to retire early or be less profitable. If that feature of industrial plants termed "vintage" proved to be a good indicator of the plants' relative energy efficiency, vintage data would be useful in a number of ways. For example, these data could be used to forecast the increase in energy efficiency and the decrease in associated pollutant emissions that might result from retiring older facilities, or they could be used to forecast the effects that various regulations associated with improving energy efficiency and reducing emissions might have on an aging industrial infrastructure.

To the extent that the industrial structure, rate of growth, and investments (i.e., capital stock turnover) determine the rate of change in industrial environmental performance and energy efficiency, one can, by analyzing vintage and performance data, gain a better understanding of the speed with which industry can adapt to policies that encourage efficiency and emission improvements through plant turnover (e.g., carbon taxes or investment subsidies and tax credits). The work discussed here provides the foundation for such policy-oriented analysis. This report discusses the issues that underlie the analysis of plant vintage and performance and provides results calculated from plant-level data.

¹ Throughout this report, the terms "plant," "establishment," and "facility" are used synonymously. Although multiestablishment plants do exist, it was not necessary to make this distinction for this report. The establishment-level data employed here represent the most disaggregated (i.e., smallest or lowest-level) unit of operation that is available for studying vintage effects. The terms "industry" and "industrial sector" refer to the manufacturing industry.

At the outset of this study, the plan was to examine the relationship of plant vintage to both energy use and emissions of pollutants into the environment. However, data from work by the U.S. Bureau of the Census (hereinafter referred to as the Bureau), in which pollutant emissions data were matched with its energy and economic data, were not available. Thus, an explicit analysis of actual emissions data could not be performed.² However, in the manufacturing industry, energy use is responsible for a large percentage of the criteria air pollutant emissions. Therefore, energy use could be used as a proxy for environmental performance. Within a global climate context, this proxy is quite accurate, because emissions of carbon dioxide (CO₂) — which contribute to global warming — result directly from the combustion of fossil fuels by the manufacturing sector and indirectly from the production of electricity by the utility sector to satisfy industrial plant demands. The fuel mix used by plants and the utility industry is the only factor that affects (directly or indirectly) the average carbon content of energy consumed (i.e., the CO₂/Btu emission rate). Emissions of criteria air pollutants also result from fuel combustion by manufacturing plants and the utility sector. If pollution control measures are used to meet environmental regulations, these emission rates can vary. Because an explicit analysis of emissions and emission rates could not be performed, this report examines pollution abatement costs across different plant vintages.

This report first examines six of the most energy intensive industrial sectors at the four-digit SIC level: 2621 — paper mills, except building paper; 2812 — alkalies and chlorine; 2873 — nitrogenous fertilizers; 3241 — cement, hydraulic; 3312 — blast furnaces and steel mills; and 3334 — primary aluminum. It focuses on two sectors — the steel and cement industries — because the installation dates for major items of equipment in these sectors (i.e., steel furnaces and cement kilns) were available from external, nongovernmental sources.³ The installation dates were used to assign vintages to plants. The report then examines the construction of alternative vintage measures, based exclusively on the Bureau's data, for the cement sector. A comparison of vintage data from the Bureau with external vintage measures could allow vintages to be assigned to plants in other sectors for which external data are not available. Finally, the report describes an additional analysis performed for a subsector of the steel industry, in which the vintage estimate obtained from the plant-level data is compared with a similar estimate from published engineering studies.

The report concentrates on two areas:

- Alternative definitions of plant vintage, the vintage distribution of capital (or capacity) by industry, and the relative utilization of different vintages; and

² This work was to be funded by a Congressional line item within the Bureau's budget. This funding was eliminated in House/Senate conference. The work has continued, but at a much slower pace.

³ Similar data for the paper industry were identified, but they were not in a format that was amenable to being matched with the Bureau's data.

- Descriptions of the relationship between vintage and energy intensity and between vintage and the intensity of pollution control expenditures.

The first task was to measure vintage. Section 1.1 discusses a vintage accounting framework. The plant-level data used as the basis for the accounting framework are described in Section 1.2. Section 2 takes a simple look at vintage, based on newly opened plants, for all six industries. A series of descriptive analyses are then presented to determine whether vintage, energy intensity, and pollution control activities are related. Subsequent sections provide more details on the issues raised by the accounting framework and present the results from applying the framework to data from the cement and steel manufacturing industries. The data used to prepare all the figures found throughout this report appear in tables in Appendix A.

1.1 VINTAGE ACCOUNTING FRAMEWORK⁴

The average energy intensity of an industry, I , at some point in time, t , has three components: (1) vintage energy intensity, (2) vintage capital utilization (relative to average capital utilization in the manufacturing industry), and (3) vintage capital proportion. This framework can be derived from the following accounting identity:

$$I_t = \frac{E_n + E_{n+1} + \dots + E_t}{Y_n + Y_{n+1} + \dots + Y_t}, \quad (1)$$

where:

E = energy use in all plants in the designated vintage class,

Y = output of all plants in the designated vintage class, and

subscripts = plant vintage.

Equation 1 can be written as follows:

$$I_t = \frac{\frac{E_n}{t}}{\sum_{i=n} Y_i} + \frac{\frac{E_{n+1}}{t}}{\sum_{i=n} Y_i} + \dots + \frac{\frac{E_t}{t}}{\sum_{i=n} Y_i} \quad (2)$$

⁴ Discussion is derived from Peck et al. (1988).

If K is defined as capital of the designated vintage class and if this vintage class term is multiplied by $Y_k K_k \sum_{i=n}^t K_i / Y_k K_k \sum_{i=n}^t K_i = 1$, Equation 2 can be rewritten as follows:

$$I_t = \frac{E_n}{\sum_{i=n}^t Y_i} \frac{Y_n K_n \sum_{i=n}^t K_i}{Y_n K_n \sum_{i=n}^t K_i} + \dots + \frac{E_k}{\sum_{i=n}^t Y_i} \frac{Y_k K_k \sum_{i=n}^t K_i}{Y_k K_k \sum_{i=n}^t K_i} + \dots + \frac{E_t}{\sum_{i=n}^t Y_i} \frac{Y_t K_t \sum_{i=n}^t K_i}{Y_t K_t \sum_{i=n}^t K_i} \quad (3)$$

Equation 3 can be rearranged to yield:

$$I_t = \frac{E_n}{Y_n} \times \frac{Y_n / K_n}{\sum_{i=n}^t Y_i / \sum_{i=n}^t K_i} \times \frac{K_n}{\sum_{i=n}^t K_i} + \dots + \frac{E_t}{Y_t} \times \frac{Y_t / K_t}{\sum_{i=n}^t Y_i / \sum_{i=n}^t K_i} \times \frac{K_t}{\sum_{i=n}^t K_i} \quad (4)$$

Equation 4 represents each vintage's contribution to the industry average as the product of three factors. The first factor is energy intensity of the v^{th} vintage at time t :

$$EI_{v,t} = \frac{E_v}{Y_v} \quad (5)$$

The second factor is the (relative) capacity utilization (i.e., the ratio of output to capital relative to the ratio of total output to total capital) for the v^{th} vintage at time t :

$$U_{v,t} = \frac{Y_v / K_v}{\sum_{i=n}^t Y_i / \sum_{i=n}^t K_i} \quad (6)$$

The last factor refers to the v^{th} vintage share of capital at time t :

$$S_{v,t} = \frac{K_v}{\sum_{i=n}^t K_i} \quad (7)$$

An industry's energy intensity is influenced by (1) the energy intensity of any particular item of equipment,⁵ (2) the degree to which this equipment is used (i.e., how much more or less it is used than other pieces of equipment), and (3) how much of the total industry capital stock that this equipment represents:

$$I_t = \sum_{v=n}^t EI_{v,t} \times U_{v,t} \times S_{v,t} \quad . \quad (8)$$

If the observed data were to accurately reveal the output and energy use of each item of equipment and if it were possible to measure the contribution of each piece of equipment to the industry's capacity or capital stock, this framework would be quite accurate. However, studies based on aggregate data cannot determine output and energy use for each item of equipment, nor can they measure the contributions of each aspect of the industry's capacity or capital stock. This study, because it is based on plant-level data, comes closer to meeting the conditions necessary to make the framework accurate.

On the other hand, plant-level data from the Bureau do not directly measure plant vintage. Several other sources could be used to measure vintage. To measure energy intensity and make interplant comparisons, physical production might be a better output measure (Y_t) than value of shipments, which is the measure used for the Bureau's data. If physical production is to be used, the plants must represent a homogeneous sample. The results that follow suggest it is worthwhile to disaggregate the four-digit plants into even smaller subsamples. Without this disaggregation, the vintage accounting framework could, in itself, be misleading. Data for capital stock, K_t , could come from the Bureau's data (i.e., be defined as the deflated book value of the plant) or be an engineering measure of capacity.

Subsequent sections of this report present results from applying this framework to data from the cement and steel mill industries and discuss problems and issues that arise in using this approach. Alternative definitions of vintage and capital stock are employed, and some conclusions about the cement and steel industries are made. To examine the output measurement and disaggregation issue, a more detailed analytic approach is taken to the steel industry results. The next section discusses the data employed in this work.

1.2 OVERVIEW OF PLANT-LEVEL DATA

The plant-level data considered for this project came primarily from three sources: the Annual Survey of Manufactures (ASM), Census of Manufactures (CM), and Manufacturing Energy Consumption Survey (MECS). Data for all three sources are collected by the Bureau to compile industrywide and economywide aggregate figures on activity in the manufacturing sector. The data are released to the public in a variety of reports. The Bureau's Center for Economic Studies (CES), through its program of Census Fellows and

⁵ Whether this ratio should be viewed as a constant coefficient is discussed later in this report.

Special Sworn Employees (SSEs), provides access to the underlying data. SSEs have complete access to the plant-level information collected by the Bureau but are required to sign a statement that they will not disclose these data. Yet, by its very existence, the CES encourages research on economic and modeling issues that involve plant-level data. Thus, the results of any analysis (including those presented in this report) based on CES-compiled plant-level data are reviewed for confidentiality disclosure. This type of review generally requires that any aggregate statistics compiled by researchers at the CES for publication or outside release cover at least six plants. Other types of behavioral (statistical) relationships are also reviewed by CES to ensure they do not violate confidentiality.

Data from the ASM and CM have been linked together in the Longitudinal Research Database (LRD), which is maintained at the Bureau. The LRD contains data from the CM for the years 1963, 1967, 1972, 1977, 1982, and 1987 and data taken from the ASM for all years not covered by the CM from 1973 through 1989. At present, the LRD has substantially more than 2 million manufacturing plant-year records,⁶ including information on more than 800,000 different plants for the 1963-1989 period. The existence of plant identification numbers makes it possible to link the LRD with the MECS; the database that consists of the MECS and LRD linked together is referred to as the MECS/LRD (Boyd et al. 1992).

Other data can be linked to the LRD as well. Any public data that identify an establishment by company name and address can, in principle, be linked to the appropriate CM year or ASM year if the establishment is in the sample. This report presents results obtained from studies of the cement manufacturing (SIC 3241) and steel manufacturing (SIC 3312) industries. The LRD data are supplemented by cement trade association data compiled by David Rosenbaum and by a steel industry database assembled by Stephen Karlson. This approach was taken so the LRD data could be supplemented with trade association data on installation dates of major pieces of equipment and engineering-based capacities.

Table 1.1 summarizes the sample of plants in the cement industry. These raw (unweighted) data represent the plants available for this analysis; they do not necessarily represent industry totals. For example, in 1987, the entire industry comprised 174 plants with a total production of 90.4 million tons. There were between 84 and 96 plants in the sample for all years except 1979, 1980, 1981, and 1983. The Bureau changed the sample frame in those years, resulting in samples that had fewer plants, but most of them had larger capacities. The census years (1977, 1982, and 1987) reflect complete counts, adjusted to allow the data to be linked with trade association data. Data from these years are used later in this report to provide "snapshots" of plant-level capacities and utilization distributions. Output is represented by the value of shipments (millions of 1982 dollars obtained with a gross national product [GNP] deflator). Capital stock data are also in constant 1982 dollars. They represent net stock depreciated for tax purposes, deflated for this report by using a capital deflator specific to four-digit SIC industries (Gray 1989). Before being deflated, data

⁶ A plant-year record is one observation of a single year's worth of data for a plant.

TABLE 1.1 Summary Sample Statistics for the Cement Industry

Year	No. of Plants	Total Output (10 ⁶ 1982 \$)	Total Capital Stock (10 ⁶ 1982 \$)	Total Capacity (10 ⁶ tons)
1974	87	2,676.9	3,608.2	55.8
1975	88	2,534.0	3,127.7	58.3
1976	88	2,643.2	2,897.3	59.7
1977	87	2,914.6	2,733.9	59.1
1978	89	3,226.4	2,538.0	60.5
1979	42	2,059.7	1,241.6	34.3
1980	42	1,825.4	1,164.2	34.3
1981	42	1,735.6	1,116.8	35.3
1982	90	2,439.4	1,752.9	62.5
1983	47	1,573.7	1,202.5	39.0
1984	85	2,592.9	2,074.6	60.3
1985	84	2,685.4	2,045.9	59.8
1986	87	2,679.5	2,140.5	60.8
1987	96	2,753.9	2,143.1	64.5
1988	85	2,507.3	1,436.6	59.8

for these two series are taken from the LRD. Data on total capacity, taken from trade association data, are defined as the total capacity of all operating kilns at the plant, measured in tons of cement per year.

Measures of labor, energy, and material inputs were extracted from the LRD for the steel industry study. Karlson's database provides measures for capacity, furnace vintages, and volume of steel produced, and data on the type of furnaces used in each plant. Tables 1.2 and 1.3 provide data on the number of plants and two output and capital measures for two samples of the industry: (1) all of SIC 3312 and (2) minimills that use electric arc furnaces (EAFs) and produce a narrow range of products. These samples are discussed in more detail in Section 4.

Capacity and production data are a subset of plant-specific estimates of capacity and output at the 165 steel plants that operated in the United States between 1970 and 1990. *The Directory of Iron and Steel Works of the United States and Canada* (institute directory), published by the American Iron and Steel Institute in 1970, 1974, 1977, 1980, and 1984, and *Iron and Steel Plants* (association directory), published by the Association of Iron and Steel Engineers every year, are the principal sources for identifying the plants in operation in a given year. The institute directory lists the iron-making and steel-making furnaces

TABLE 1.2 Summary Sample Statistics for the Steel Industry

Year	No. of Plants	Karlson Data (10 ⁶ tons)		LRD Data (10 ⁹ 1982 \$)	
		Output	Capacity	Output	Capital Stock
1972	333	10.9	14.5	52.0	58.2
1973	255	12.9	15.2	60.6	54.2
1974	262	12.5	15.2	77.2	47.3
1975	283	10.0	15.3	61.4	39.1
1976	283	11.0	15.2	63.8	36.8
1977	280	10.6	15.1	61.4	32.6
1978	253	12.0	14.8	68.4	29.6
1979	217	12.0	14.8	70.7	25.7
1980	215	9.8	14.5	58.2	22.4
1981	214	10.6	14.2	60.8	20.2
1982	285	6.6	13.4	34.8	19.3
1983	184	7.4	12.7	34.1	17.5
1984	177	8.7	13.0	36.8	15.9
1985	179	8.3	12.4	33.1	15.8
1986	173	7.5	11.4	29.4	15.1
1987	342	7.8	10.4	32.9	13.2
1988	167	8.7	10.5	39.0	14.3

present at each plant. Some association directory entries list plant capacities. The complete inventory of steel-making capacity at all U.S. plants begins with information published in Deily (1980) and is extended after 1979 with capacity reports found occasionally in *Iron Age* published by Chilton or in *Iron and Steel Engineer* published by the Institute for Iron and Steel Studies and with EAF roundups found annually since 1987 in *Iron and Steelmaker* published by the Iron and Steel Society. Estimates of plant-specific production begin with raw steel production statistics found in various issues of the *Annual Statistical Report* published by the American Iron and Steel Institute. This institute reports data on nationwide raw steel production disaggregated by state (for the major steel-producing states) and groups of states (for those states that have few steel producers). The state totals are one set of control totals used to check the validity of estimates.

The second set of control totals consists of company-specific production totals that were reported on until the end of 1984 in the "Steel Industry Financial Analysis" published in *Iron Age*. Those totals are extended with production data found in *Metal Statistics* published by American Metal Markets; information found in industrial manuals published by Moody's Investors Service, Inc.; data found in corporation records and stock price reports

TABLE 1.3 Summary Sample Statistics for Steel Industry Minimills that Use Only Electric Arc Furnaces

Year	No. of Plants	Karlson Data (10 ⁶ tons)		LRD Data (10 ⁹ 1982 \$)	
		Output	Capacity	Output	Capital Stock
1972	17	5.6	7.3	1.8	1.4
1973	20	7.0	8.5	2.4	1.6
1974	19	7.3	8.8	3.4	1.6
1975	18	6.7	10.1	2.6	1.3
1976	21	6.5	10.8	2.6	1.4
1977	23	8.1	12.4	2.7	1.5
1978	24	10.1	12.9	3.6	1.5
1979	24	10.8	13.5	4.1	1.3
1980	23	10.1	13.2	3.5	1.2
1981	23	10.6	14.3	3.7	1.2
1982	23	7.5	14.1	2.3	1.0
1983	27	8.8	15.8	2.5	1.1
1984	25	10.6	15.4	3.0	1.1
1985	28	10.9	16.6	2.9	1.1
1986	27	11.6	16.5	3.0	0.9
1987	25	11.3	13.9	2.9	0.8
1988	25	11.8	13.3	3.3	1.3

published by Standard and Poor's Corporation; and data found in *Iron and Steel Engineer* published by the Institute for Iron and Steel Studies. These reports identify the exact output from six or seven plants. The reported company-specific totals make up two-thirds to four-fifths of total U.S. steel production in each year. That output is allocated among the reporting company plants. The difference between total U.S. production and reported production is output to be allocated among nonreporting company plants.

This allocation of output allows an initial estimate of each plant's production to be computed on the basis of its capacity. For reporting company plants, the estimate of a plant's output is the same as the proportion of capacity that the plant represents in the total capacity of its company in that year. For nonreporting plants, the estimate of a plant's output is the same as the proportion of capacity that the plant represents in the total capacity of all nonreporting companies. The estimates are then adjusted to satisfy the state production totals. Estimates are updated until the outputs of each plant satisfy both the state production total and the relevant reporting or nonreporting company production total

for that year.⁷ With an accounting framework and a data set established, the next step is to develop measures of vintage. This procedure is discussed in Section 2.

⁷ The method is the same method Karlson (1980) used to estimate outputs from fully integrated steel plants for 1972. The capacity and production data underlie empirical research reported in Karlson (1983, 1986).

2 PLANT VINTAGE

On a conceptual level, the vintage of a plant may be difficult to identify. Even when the term "vintage" is carefully defined, vintage may be difficult to measure in practice. This section discusses the various approaches that can be taken to assign a measure for plant vintage and examines how a plant's vintage can be defined in terms of data found in the LRD and other sources.

2.1 ANALYSIS OF NEW PLANT PERFORMANCE

One expects the vintage of a plant to represent the state of technology on which a decision maker bases a determination of how a plant should produce output. When a plant is new, vintage represents the latest technology or current "best practice" technology.⁸ In this case, it is easy to assign a measure for vintage — usually the date (year) the plant was built or opened. If nothing ever changes in the plant — if no new equipment is added or if no inventions are applied by employees — vintage may be adequately represented by the date the plant opened. However, this situation rarely occurs.

Although this case is unlikely, making an assumption that when a plant opens, its vintage is a well-defined notion, allows certain comparisons to be made. Simple questions can be asked, such as, "Do new plants perform better than old plants?"⁹ The difficulty arises in determining what is meant by "new" and "old." Does "old" mean last year's plants and "new" mean this year's plants? Or does one look at five-year groups? Ten-year groups? Variations in operating practices may make it difficult to identify small changes, such as those that occur year to year; however, larger changes, such as those that occur over a 10-year period, may be identifiable.

This section examines the average energy intensity of greenfield (i.e., entirely new) plants in six four-digit industries. Both fossil fuel and electricity intensities that represent each industry's average intensity are compared with the intensities of new plants that opened in the 1963-1972 and 1973-1987 periods. Energy intensities for plants that were permanently closed are also examined. Although the plants that were closed were not necessarily the oldest plants, they were, by definition, economically obsolete. Plants that were shut down temporarily are examined as well.

Electricity intensity is the ratio of electricity consumption (in kilowatt-hours) to value of shipments (deflated with a GNP deflator). In each case, the average over the time period is shown. For example, for greenfield plants that were opened from 1963 through 1972, the average intensity for the period lasting from the year the plant opened through 1972 is shown. Fossil fuel intensity, which is the ratio of the cost of fuels to the value of shipments,

⁸ Possible departure from best practice is discussed in Section 3.

⁹ How performance is defined is discussed in Section 3.

is handled similarly. The cost of fuels is deflated with a price index for fossil fuels that is unique to the four-digit SIC industry. Because of the (1) extended time periods involved, (2) variability between actual plant-level prices and national deflators, and (3) inhomogeneities in certain industries (e.g., paper, steel, and fertilizers), the energy intensity distributions consisting of plant-year points are broad. The standard deviations are comparable to the mean values.

Table 2.1 shows the average energy intensities for the plants in the six industries. Data are provided for the industry average of all plants, three classes of greenfield plants (those that opened after 1963, those that opened between 1963 and 1972, and those that opened between 1972 and 1987), and two classes of closed plants (those that permanently closed after 1963 and those that closed temporarily from 1963-1987). The data on greenfield and closed plants is taken from the CM years, based on the LRD coverage code. The code explicitly identifies which facilities are greenfield and which are closed.

TABLE 2.1 Mean Energy Intensities of Greenfield Plants and Closed Plants for Six Industries

SIC and Industry	Energy Type	All Plants	Greenfield Plants Opened			Old Plants Closed	
			Post 1963	1963-1972	1973-1987	Permanently	Temporarily
2621 Paper	Electricity	2.35	3.77	2.79	4.88	2.34	1.94
	Fossil fuel	0.035	0.037	0.043	0.031	0.048	0.038
2812 Alkalies	Electricity	15.32	14.18	W ^a	W	W	W
	Fossil fuel	0.055	0.055	W	W	W	W
2873 Fertilizer	Electricity	3.86	3.28	3.98	2.42	5.00	5.62
	Fossil fuel	0.090	0.108	0.087	0.133	0.164	0.076
3241 Cement	Electricity	2.22	1.96	2.31	1.56	2.15	1.90
	Fossil fuel	0.102	0.078	0.101	0.051	0.126	0.103
3312 Steel	Electricity	2.41	3.42	3.61	3.28	1.69	2.35
	Fossil fuel	0.027	0.015	0.014	0.016	0.030	0.054
3334 Aluminum	Electricity	26.56	27.10	W	W	24.51	W
	Fossil fuel ^b						

^a W = withheld because of the Bureau's disclosure rules.

^b Use of fossil fuel in the primary aluminum industry is not reported, since it represents only a very minor portion of total energy use in this industry.

For plants that were opened after 1963, those in the paper and steel industries have higher electricity intensities, reflecting an increased penetration of electric processes in these sectors (especially thermomechanical pulping in the paper industry and the use of EAFs in the steel industry). Fertilizer and cement plants have lower electricity intensities. When the class of new plants is broken down further (as shown), these two trends are at least as great or even more pronounced. Permanently closed fertilizer plants have higher electricity intensities, while closed steel plants have lower electricity intensities.

Different intensity patterns emerge for fossil fuels. Of the plants that were opened after 1963, fossil fuel intensities are lower only in the cement and steel industries.¹⁰ (The fossil fuels consumed in the steel industry do not include metallurgical coal or its by-products.) Fertilizer plants have higher intensities, but the accuracy of this result is obscured by feedstock issues (i.e., the use of natural gas in forming ammonia) that were not treated in detail. For plants that were opened after 1973, those in the paper industry exhibit lower fossil fuel intensities as well. These lower intensities are presumably associated with the strong trend to substitute biomass for fossil fuels in the paper industry. Plants that were closed in the paper, fertilizer, and cement industries have higher fossil fuel intensities, as do the temporarily closed plants in the steel industry.

The analysis of new plants allows the researcher to view one simple dimension of the effect of vintage on energy use. Some energy intensity patterns for new plants in the paper, steel, and cement industry are consistent with expectations. Very little can be inferred from the results for the aluminum and chlorine sectors. The analysis for fertilizer plants needs to incorporate a more detailed accounting of feedstock energy use. Overall, the analysis suggests that energy use in new plants is consistent with expectations, but it does not provide the more complete overview described in Section 1.2. To do so, a more thorough measure of vintage must be developed. The next section addresses this issue.

2.2 ALTERNATIVE VINTAGE MEASURES

In the previous section, the energy intensities of completely new plants were identified and compared with the industry average energy intensity. New plants represent a special case of the vintage effect, since all the technology in the plant is assumed to be the most current available. However, typical plants are not homogenous commodities; they represent unique collections of people and things (labor and capital) as well as unique knowledge about how to combine these people and things to produce something. If one could assume that a particular item of equipment embodies a certain level of technology when purchased, it could be useful to use the major equipment in a plant to determine the vintage of the plant. However, even when such data are available, there are several alternative approaches to assigning plant vintage.

¹⁰ Use of fossil fuel in the primary aluminum industry is not reported, since it represents only a very minor portion of total energy use in this industry.

If the key items of capital equipment in a plant or process can be identified, one might say that the plant is "updated" to the current vintage when a new piece of this equipment is installed. If the technology in a particular industry changes in discrete steps, this approach might be adequate. It might work well for some process industries, such as cement and aluminum, with their associated kilns and smelter lines.

This approach is less likely to work well if the technology in an industry changes gradually. In this case, new equipment represents only an incremental improvement and might operate beside older equipment. In industries in which processes are very complex and in which each item of equipment represents one step and interacts with both newer and older vintages of equipment (such as the paper and steel industries and some chemical sectors), this approach to assigning plant vintage may not be effective. On the other hand, perhaps many of the improvements that make a machine manufactured in 1992 more productive than its 1972 equivalent can be fitted to the 1972 machine, and perhaps the workers in this more complicated industry are familiar with the latest techniques.

The ability to assign vintages on the basis of major items of process equipment depends on data external to the LRD. The first phase of this analysis uses such external data, and the results described in this report are based on these data. The major process step in cement making occurs at the kiln; a major process step in steel making occurs at the steel-making furnace. The basic approach for assigning a vintage to a steel or cement plant is to use data on the installation dates and capacities of its newest kilns or furnaces. These data come from the sources described above. The resulting measure will be referred to here as simply the vintage. Besides its simplicity, this approach has another advantage; it tends to underestimate the vintage effect. Any relationship between performance and vintage that actually occurs is likely to be at least as close as the relationship predicted by this simple approach.

A second approach uses capacity-weighted average installation dates to define vintage. It will be compared with the simpler approach. The capacity-weighted vintage of a plant that has two kilns of identical capacity — one installed in 1960 and one installed in 1980 — is 1970.

When external data are not available, other approaches are required. One approach assigns an investment-weighted year as the vintage. The result is the net-investment vintage. This approach uses data on the entire investment history of the plant. To assess the approach, this report examines the investment history of cement plants at five-year intervals. The intervals are CM years (i.e., 1963, 1967, 1972, 1977, 1982, and 1987).¹¹ A weight is assigned to each plant on the basis of the change of the deflated book value of assets in that year (see Appendix B for details and an example). This approach uses net investment to assign plant vintage (i.e., when a plant expands, its vintage changes). To capture replacement investment as well as net expansion of a plant, a gross investment

¹¹ The first year for which CM data are available in an electronic format is 1963. The CM has been conducted every five years since 1967.

approach is required. This gross-investment vintage is also examined. To construct the gross investment index, a subsample of plants that have data for every year from 1972-1988 is used.

One question that arises with respect to these alternative measures of vintage has to do with how similar they are. The second question that arises is whether the same qualitative observations regarding vintage and performance can be made when alternative definitions of vintage are used. To answer the first question, Spearman correlation coefficients between the four measures of vintage are computed. The first measure is based on the year of the newest kiln, VINT. The second measure is based on the capacity-weighted average of the kiln installation date, VINT₁. The third measure is the vintage index based on net investment alone (taken from CM data), VININDEX^{NET}. The last measure is an index based on gross investment (taken from a subsample of plants for which continuous annual data were available), VININDEX^{GROSS}. The results are shown in Table 2.2. The high correlation between VINT and VINT₁ was expected. The most interesting result is the correlation between VINT/VINT₁ and VININDEX^{NET}. Given that VININDEX^{NET} is not based on annual changes, its 45-51% correlation is encouraging, but it is still not as good as one might like. The correlation of the gross-investment-based index, VININDEX^{GROSS}, with VINT and VINT₁ is even lower. This result is not surprising when one considers that a kiln installation is an infrequent and large net plant investment and, as such, is included in VININDEX^{GROSS}. However, VININDEX^{GROSS} includes many other categories of plant investment as well. Clearly, many factors other than the kilns determine the book value of assets and give rise to different plant vintage assignments. VINT is used as the primary vintage measure in this report, but the qualitative impact of these alternative indices on energy intensity distributions is examined in Section 4.

2.3 VINTAGE DISTRIBUTIONS

This section discusses the vintage distributions of capacity and capital stock for the cement and steel industries. Data are presented as a series of snapshots for the CM years. This choice of census years reduces sample bias in these distributions.

TABLE 2.2 Spearman Correlation Coefficients between Measures of Plant Vintage for the Cement Industry

Measure	Correlation Coefficient between Measure Below and Measure at Left ^a	
	VINT	VINT ₁
VINT ₁	0.92	
VININDEX ^{NET}	0.45	0.51
VININDEX ^{GROSS}	0.24	0.23

^a All coefficients are significant at a 0.01 confidence level.

2.3.1 Cement

The plant vintage capacity distributions for 1977, 1982, and 1987 are shown in Figure 2.1.¹² This figure indicates how the vintage distribution of the cement industry evolved over time. Some earlier vintage plants were updated to become new vintage plants, some older plants were permanently closed, and some new plants were opened. All of these events contributed to the changing vintage distribution. The LRD contains data on capital stock, a dollar measure of the value of a plant and its equipment. These data should be closely related to the capacity of the plant. If they are not, some explanation is required. Vintage distribution of capital stock is shown in Figure 2.2. These two approaches to measuring the size of the plant (i.e., capacity or capital stock) produce very similar results.

Another measure of vintage distribution can be derived from these data. In the figures, plants were grouped into three-year vintage classes to help solve problems related to disclosing and reporting data on individual plants. However, a public source was used to obtain data on kiln capacity and dates of kiln installations. On the basis of these data, vintage distributions could be reported on an annual basis rather than a three-year basis without breaking disclosure requirements. Annual vintage distributions are shown in Figure 2.3. The only particularly revealing observation one could make from studying this figure is that kiln installations appear to be quite cyclic, with distinct boom and bust years reflected in major capacity changes. A study of how the kiln installation data relate to business cycles might help to reveal how the cement industry expands and contracts.

2.3.2 Steel

Vintage distributions of capacity for 1972, 1977, 1982, and 1987 are shown in Figure 2.4. Older plants survived throughout the sample period, but plants in the 1969-1972 vintage class declined in importance as they were closed or upgraded to newer vintages. Figure 2.5 for capital stock exhibits a similar pattern. It shows how market niches can prevent older plants from closing and that retirement and replacement do not always occur in the oldest categories.

2.4 RELATIVE VINTAGE UTILIZATION

In the accounting framework presented in Section 1, the relative energy use of the different vintages was shown to contribute to the average industry input (energy) intensity. If the manufacturing sector were to use efficient plants (that use less energy) more and

¹² Currently, kiln-level data to identify vintage are available to 1984. Vintage effects for 1985, 1986, and 1987 are not captured.

FIGURE 2.1 Vintage Capacity Distributions for Cement Plants (Source: Table A.1)

FIGURE 2.2 Vintage Capital Stock Distributions for Cement Plants (Source: Table A.2)

FIGURE 2.3 Annual Vintage Capital Stock Distributions for Cement Plants (Source: Annual data used as the basis for this figure are not available for publication because of the Bureau's disclosure rules)

FIGURE 2.4 Vintage Capacity Distributions for Steel Plants (Source: Table A.3)

FIGURE 2.5 Vintage Capital Stock Distributions for Steel Plants (Source: Table A.4)

inefficient plants (that use more energy) less, its overall energy intensity would be lower. The vintage distribution of relative utilization can be represented as follows:

$$\frac{Y_t/K_t}{\frac{\sum_{i=0}^T Y_i / \sum_{i=0}^T K_i} , \quad (9)$$

where the numerator represents the t^{th} vintage utilization and the dominator is the industry average utilization. This index is greater than one if plants of a particular vintage are used more than average; it is less than one if they are used less often than average.

2.4.1 Cement

Figure 2.6 indicates the relative utilization of kiln capacity, K_t . Although there appears to be a slight downward trend in 1977, no such pattern appears in later years. The same is true when K_t is defined as total capital stock (Figure 2.5). However, a comparison of Figures 2.6 and 2.7 shows there is actually little similarity between the two distributions. Although the vintage stock/capacity distributions seem unaffected by the definition of K_t , the relative utilization index is quite sensitive to how K_t is defined.

These results appear to repudiate the economic ordering of cement plants by vintage (i.e., using efficient plants more than less efficient plants when operating at less than full capacity). The reason is either because the older plants are not less efficient or because economic ordering does not occur in the industry. One major reason to suspect that the latter case is true is the distinctly regional nature of cement markets. Variations in regional demand that drive utilization decisions in this industry are not accounted for. Sterner remarked on this fact in his study of the Mexican cement industry as well (Sterner 1985).

2.4.2 Steel

Figure 2.8 gives the vintage relative utilization for the steel industry. As was the case for the cement industry, no clear pattern emerges. Only in 1982 does relative utilization have an upward slope. In other years, there is no systematic pattern. When K_t is defined as a measure of capital stock (see Figure 2.9), even more variability occurs. Although the steel industry is less likely to have regional market niches, it is quite likely to have product market niches. These niches would inhibit a simple, neoclassical ordering of plant utilization by vintage.

FIGURE 2.6 Vintage Relative Capacity Utilization Distributions for Cement Plants (Source: Table A.1)

FIGURE 2.7 Vintage Relative Capital Stock Utilization Distributions for Cement Plants (Source: Table A.2)

FIGURE 2.8 Vintage Relative Capacity Utilization Distributions for Steel Plants (Source: Table A.3)

FIGURE 2.9 Vintage Relative Capital Stock Utilization
Distributions for Steel Plants (Source: Table A.4)

3 ENERGY AND ENVIRONMENTAL PERFORMANCE

This section discusses the concepts that underlie the measurement of plant-level performance. The focus is on energy and environmental performance. Three approaches to assessing performance are discussed: a total factor productivity approach, a production model approach, and an efficiency approach. Although each approach views performance and vintage in a slightly different manner, the approaches share some characteristics. The overall framework must be understood as well. For example, energy is only one input in the plant production process. Another input is capital, and the long-term nature of capital investment gives rise to the notion of vintage. This section briefly discusses the economics-based language used to describe plant-level production and how the economics framework can help one understand plant-level data, plant performance, and vintage.

3.1 TOTAL FACTOR PRODUCTIVITY APPROACH

The total factor productivity (TFP) approach has been applied to assess the performance of the entire U.S. economy and individual two-digit SIC industries. Jorgenson (1987) provides a good example. The TFP approach has also been used to assess performance at the plant level in conjunction with LRD data (Bartelsman and Dhrymes 1992). The TFP approach measures increases in production that are not directly attributable to increases in capital, labor, energy, and other factors. A major issue is whether the productivity changes measured by this approach are embodied in the capital investment or neutral (i.e., represent improvements that occur without investment). (See Hulten [1992] for a discussion and model of embodiment at the aggregate level.) Neutral technical change can occur if workers and managers are simply smarter about organizing themselves and their resources to produce more with the same or fewer inputs. Embodied technical change occurs only as a result of new capital investments that are the latest technology. Embodied technical change is the essence of a vintage-driven effect on plant performance.

3.2 PRODUCTION MODEL APPROACH

The assumptions used in plant-level production models — those that describe the relationship between input mix (including energy and capital as well as all other inputs) and outputs (including pollution as well as useful products) — should be explicit. A spectrum of assumptions relevant to issues of vintage and performance includes those related to smooth factor substitution, putty clay, and fixed coefficients.

3.2.1 Smooth Factor Substitution Models

Smooth factor substitution occurs when the mix of inputs (such as capital, labor, and energy) can be smoothly adjusted to changing conditions, particularly the relative costs of these inputs. Models that employ flexible functional forms and dual cost functions typify this

smooth substitution (Jorgenson 1987 and others). Vintage effects enter these modeling approaches by adjusting the measure of capital to reflect its underlying vintage distribution. In other words, vintage enters these approaches only by changing the amount of "effective" capital available to the production process. Published measures of capital stock use this approach. Successive vintages of capital (i.e., investment that occurs in some year) are depreciated or decay according to some formula, usually a geometric one.

3.2.2 Putty-Clay Models

Putty-clay models treat the flexibility of input as a two-stage process. The first stage relates to the firm's introduction of state-of-the-art processes and cost-effective input usage in new facilities. How energy efficient should a new plant be designed to be? The range of energy-efficient investments in new plant and equipment reflects *ex ante* (i.e., before the fact) possibilities. The second stage is a retrofit issue. How much can the types and levels of energy use in existing plants and processes be changed *ex post* (after the fact?) The energy-efficiency choices available to a decision maker are delineated according to whether the decision is *ex ante* or *ex post*.

The degree of flexibility that firms have in *ex-post* energy-efficiency investments will determine how quickly and easily the industry can adjust to changing conditions (i.e., relative energy prices). *Ex ante*, firms usually have many more choices; however, the speed at which they can respond to changes in energy prices will be governed by the growth of the demand for their output and the retirement or obsolescence rate of their existing capital stock.

One simple putty-clay model is presented by Peck et al. (1988). Underlying the Peck model is the simple notion that the energy intensity of energy-using capital equipment is based on the prevailing prices of energy and other inputs at the time the investment is made. More specifically, the ratio of energy use to any other input (e.g., capital, labor, or materials) is a function of the relative prices of the respective inputs. For example, the energy-to-capital ratio for equipment installed in time period t (i.e., of vintage t) is given by:

$$\frac{E_{vint\ t}}{K_{vint\ t}} = g\left(\frac{P_E}{P_K}\right), \quad (10)$$

where:

K = capital,

E = energy use,

P = price, and

g = function whose form and parameters are specified by the user.

Model parameters are chosen by expert judgment, engineering evidence, or statistical procedures.

3.2.3 Fixed-Coefficient Models

Fixed-coefficient models are in the input-output (IO) family. They are often called Leontief models, after the founder of IO analysis. They assume that production relationships are fixed and inflexible. If a fixed IO ratio exists for different time periods, and if a fixed coefficient is embodied in the capital stock, this approach to modeling the relationship of vintage to performance is the most restrictive and extreme.

Fixed-coefficient-embodied technology would yield the most clear-cut relationship between vintage and performance. Performance is defined as the IO coefficient that completely describes that vintage. When input usage is more flexible, the vintage effect is harder to measure. When looking for evidence of a fixed-coefficient vintage relationship, one might find that as a performance measure, IO ratios might not have a simple vintage relationship. Recall Equation 8:

$$I_t = \sum_{v=n}^t EI_{v,t} \times U_{v,t} \times S_{v,t} .$$

The energy intensity ratio, $EI_{v,t}$, may not be constant as a function of t ; it can vary according to the flexibility of the production process and with process retrofits. In examining the vintage distributions of $EI_{v,t}$, one might find that the degree of variation across plants and within plants over time is important.

3.3 EFFICIENCY

The preceding discussion assumed that a plant installs the newest vintage (i.e., best equipment available) and that the new equipment is operated to its fullest advantage. However, this situation is not always true. Plants may run inefficiently because (1) they lack experienced employees, (2) they do not install the best equipment, or (3) they underutilize equipment because of short-run fluctuations in the demand for their output (e.g., because of recession). Even within a vintage class consisting of new plants, some may not realize best practice.

In Boyd et al. (1992), a method was used to identify best-practice plants. This approach can also be used to screen data and control for the effects of inefficiency on plant-level performance (e.g., energy intensity). The technique may also be used to extract the effects of vintage. This technique for identifying best-practice plants is applied to a segment of the steel industry in Section 5.

4 INPUT INTENSITY DISTRIBUTIONS

This section presents the vintage distributions for electricity intensity and fossil fuel intensity for the cement and steel industries.¹³ Vintage distributions for the intensity of pollution abatement are also examined for the sample of cement plants. The vintage distributions for intensity of pollution abatement expenditures include both capital expenditures and operating costs. The newest kiln (furnace) installation date is used to define plant vintage (i.e., VINT in Section 2). The net investment measure of vintage, VINDEXT, and the weighted capacity measure, VINT, are also studied to see if the energy intensity distributions are consistent for all definitions of vintage.

Although the accounting framework focuses on energy intensity (defined as energy/output, where input is energy and output is deflated shipments or tonnage), this report also examines other measures. One reason to look at intensity measures other than energy/output ratios is to control for capacity utilization. Energy/output ratios tend to rise when capacity utilization falls (Bock et al. 1992; Boyd et al. 1992). However, if there is no systematic dependence of utilization on vintage, and if, as suggested by the Peck model, energy use is largely related to capacity or capital stock, the energy/capital ratio might exhibit less variation and be a better indicator of vintage-based trends than the energy/output ratio. Therefore, in addition to energy/output ratios, distributions of energy/capital ratios (where capital is based on capacity or capital stock) for each of the two energy types and two pollution control expenditure types are presented in the sections that follow.

As discussed above, energy intensity is not expected to be constant for a plant. Nor are the various plants in each vintage class expected to have the same energy intensity. To represent the variation of energy intensity in each vintage class, the standard deviation as well as the mean energy intensities for each vintage class are plotted. The plots represent the mean, plus or minus one standard deviation, for all plant-years in that vintage class. These plots tend to represent the distributions as normal. Although normality may not be the case, the plots are the most readily available form to represent the distributions. The use of nonparametric methods like decile or quantile plots would avoid this problem, but when those methods are used, more data fail to satisfy U.S. Bureau of the Census disclosure restrictions.

Not only is energy intensity plotted by vintage class, a simple regression line is fit to the plant-level vintage and energy intensity data. The regression lines represent an estimate of the rate of change in energy intensity per year of vintage. They do not explain the forces that drive the change (e.g., technology improvement or energy prices). This explanation would require further analysis. The regression lines do provide a statistical

¹³ Electricity is not aggregated with fossil fuels into an energy total, since electricity and fossil fuels are used for very different purposes in both of these industries, as is the case in most energy-intensive sectors. In future analyses, carbon weights based on fossil fuel shares could be applied, and CO₂ intensity could be computed instead. This procedure would capture any vintage effects on CO₂ that are attributable to fuel switching.

measure of the significance of any trend revealed by the vintage plots. In many cases, a statistically significant vintage effect is found, but the R^2 for the entire regression run is, in all cases, very low. Although the data show that vintage has an effect, vintage explains very little of the plant-level variation in energy intensity. The data consist of plant-year points, so the variation is associated with both cross-sectional and time-series effects.

The vintage distributions of the plant-level energy intensities for electricity use are measured in kilowatt-hours per unit of output; those for fossil fuel use are measured as an implicit (Btu) quantity index per unit of output. Whenever possible, the vintage classes are defined so data do not have to be withheld to meet confidentiality restrictions. When this type of definition is not possible, the observations are withheld, which is indicated by a "W" on the plot. The regression line is shown on the plot and an accompanying table.

4.1 ENERGY INTENSITY DISTRIBUTIONS FOR THE CEMENT INDUSTRY

This section presents the energy intensity distributions for the sample of cement plants that were matched to the LRD. The energy/output ratio is based on the census data for value of shipments, corrected for changes in inventories, and deflated with the implicit GNP price deflator to yield constant 1982 dollars. The census data for expenditures on fossil fuels are deflated by a four-digit specific energy price deflator, so the fossil fuel data represent an implicit (Btu) quantity index. Electricity data (in kilowatt-hours) were taken from the U.S. Bureau of the Census. The capital stock data (the book value of plant and equipment) were taken from the LRD and deflated by a four-digit specific capital price deflator. The capacity measure is the total capacity of all kilns operating at the plant, measured in tons of clinker produced. Capacity data were taken from the trade association data compiled by David Rosenbaum.

4.1.1 Energy/Output Ratio

Figure 4.1 and Table 4.1 indicate that the trend in the mean electricity intensity for cement plants is increasing slightly (i.e., the ratio is getting slightly higher for more modern plants). This trend is consistent with general trends of electrification in many industries. The dry cement process in particular requires more preparation (grinding, etc.) and hence more electricity. No particularly wide swings in the distributions for any given vintage are observed.

An apparent downward trend in mean fossil fuel intensity for the cement industry, by vintage class, is indicated in Figure 4.1 and Table 4.1. This trend is consistent with general trends in fuel conservation and also with the introduction of the dry cement process, which uses less fossil fuel. The vintage coefficient in the regression is statistically significant. It implies a rate of decline in fossil fuel use of about 1% per year.

In interpreting these results and the associated results immediately below, one should be aware that the energy intensity data are for no earlier than 1963, and the pollution

FIGURE 4.1 Plant Energy/Output Ratio Vintage Distributions for the Cement Industry
 (Source: Table A.5)

TABLE 4.1 Regression Results for Cement Industry Energy/Output Ratio

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0309	2.57920	-28.014319 -5.471	0.015563 5.975	0.60
Fossil fuel t-ratio	0.0519	0.09870	2.020444 8.230	-0.0000978 -7.828	0.99

abatement data are for no earlier than 1979, while capacity-based vintage data are from the 1940s. Thus, plants of early vintage are represented by energy and pollution abatement data from long after they were built. Meanwhile, data for plants of more recent vintage start with the initial, or vintage, year. Therefore, there is an asymmetry in the analysis of older and newer plants, which is likely, in itself, to cause a vintage effect.

It is not apparent whether the upward trend for electricity intensity or the downward trend for fossil fuel intensity changes for vintages installed after 1974. Any decrease in the upward trend for electricity or increase in the downward trend for fossil fuel as a result of higher energy prices in the mid to late 1970s would be consistent with the putty-clay model assumptions. The simple graphs in Figure 4.1 and the regression do not reveal any acceleration of the trends seen in the pre-1970s data. Additional modeling would be required to assess the Peck model assumptions about putty-clay, technology-embodied price responses.

4.1.2 Energy/Capacity Ratio

If variations in capacity utilization cause a problem in identifying vintage-based trends, the energy/capacity ratio may help identify the trends. Figure 4.2 gives the energy/capacity ratio vintage distributions. The trends for both energy types are similar to those of Figure 4.1: downward for fossil fuel and upward for electricity. The regression results in Table 4.2 show no statistically identifiable trend for electricity, but they show a significant trend in fossil fuel use of -1.7% per year. The idea that capacity utilization contributes substantially more variation to the vintage distributions for energy/output does not seem to be true. Not only are there similar trends in mean energy intensities by vintage class, but the variations in the energy/capacity ratio appear to be comparable to the variations in the energy/output ratio.

This result for capacity utilization is consistent with observations in Das (1992) that kilns either ran at full capacity or were completely idle. Partial utilization of capacity contributes to a rising energy/output ratio. In the cement industry, partial utilization does not appear to be an issue.

FIGURE 4.2 Plant Energy/Capacity Ratio Vintage Distributions for the Cement Industry
(Source: Table A.6)

**TABLE 4.2 Regression Results for Cement Industry
Energy/Capacity Ratio**

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0000	116.30678	129.621192 0.568	-0.006773 -0.058	0.006
Fossil fuel t-ratio	0.1092	4.65900	161.705360 12.060	-0.079892 -11.712	-1.7

4.1.3 Energy/Capital Stock Ratio

Section 2 showed alternative ways to define capital (K_t) in the framework. In addition to capacity, vintage distributions of the energy/capital stock ratio can be examined for the sample of cement plants. Capital stock includes categories of investment that are not directly related to the high-energy-using portions of the plant (e.g., trucks, offices, areas that load and unload equipment). Given the results related to capacity in Section 4.1.2, one might expect this ratio to vary more. The expected high variation is evident for the electricity/capital stock ratio but less evident for the fossil fuel/capital stock ratio. This result suggests that care must be taken in using capital stock data to define capacity when no external trade association data are available.

Table 4.3 shows there is no statistical trend in the electricity/stock ratio, but there is a significant trend (a decline of about 2% per year) in the fossil fuel ratio. Almost no trend is discernable in the vintage plot for the electricity ratio in Figure 4.3. The variation exceeds the mean for some classes. A downward trend is still visible in the fossil fuel distributions, which is also borne out by the statistical analysis.

**TABLE 4.3 Regression Results for Cement Industry
Energy/Capital Stock Ratio**

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0006	4.36061	59.242454 0.909	-0.027919 -0.842	-0.24
Fossil fuel t-ratio	0.0425	0.14729	5.719945 7.200	-0.002835 -7.015	-1.92

FIGURE 4.3 Plant Energy/Capital Stock Ratio Vintage Distributions for the Cement Industry (Source: Table A.7)

4.2 ENERGY INTENSITY DISTRIBUTIONS FOR THE STEEL INDUSTRY

This section presents the energy intensity distributions for the sample of steel plants that were matched to the LRD. The output value in the energy/output ratio is based on production data (measured in tons) compiled by Karlson as well as the Bureau's data on dollar value of shipments (in constant 1982 dollars based on a GNP deflator). Fossil fuel use is based on expenditure data taken from the Bureau and deflated with a four-digit SIC energy price deflator to yield an implicit (Btu) quantity index (Gray 1989). Electricity data (in kilowatt-hours) were taken from the Bureau. The capital stock data (the book value of plant and equipment) were taken from the LRD and deflated with a price index for capital for the four-digit SIC (Gray 1989). The capacity measure is the total capacity of all steel-making furnaces operating at the plant, measured in tons of raw steel produced. Capacity data were taken from data compiled by Karlson.

As in Section 4.1, both vintage distribution plots and simple regression results are shown. In many cases, a statistically significant vintage effect is found, but, as for cement, very little of the cross-sectional and time-series plant-level variation is explained by vintage alone.

4.2.1 Energy/Output Ratio

Table 4.4 and Figure 4.4 show the energy/output distributions, where output is defined by the constant (1982) dollar value of shipments. For plants in the late-1970 vintage classes, electricity intensity appears to rise dramatically. This trend probably reflects the fact that large EAFs were installed during that time. The regression results show a significant (2.26% per year) increase in vintage electricity intensity. The trend for fossil fuel use is small and not significant.

**TABLE 4.4 Regression Results for Steel Industry
Energy/Output Ratio**

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0735	4.11731	-179.1869 -9.502	0.093054 9.720	2.26
Fossil fuel t-ratio	0.0008	0.02665	0.164572 1.144	-0.000070015 0.959	-0.26

FIGURE 4.4 Plant Energy/Output Ratio Vintage Distributions for the Steel Industry
(Source: Table A.8)

Several of the vintage classes have distributions that include values below zero (i.e., standard deviations that exceed the mean). This fact does not imply that some plants have negative energy intensity but rather that the variation in those classes is very large. This result is important since it suggests that many vintage classes do not contain a homogeneous sample of plants.

4.2.2 Energy/Capacity Ratio

Table 4.5 and Figure 4.5 show energy intensity in terms of furnace capacity instead of production output. The idea behind using capacity rather than output is to control for capacity utilization. The variation in the electricity/capacity ratio is much larger than that in the electricity/output ratios and reveals a different trend. The electricity intensity of capacity is falling by 0.7% for each vintage year (i.e., per year as plants become newer). Fossil fuel use exhibits an even larger decline, almost 3% per year. Both of these trends are significant.

4.2.3 Energy/Capital Stock Ratio

Table 4.6 and Figure 4.6 examine energy intensity in terms of the plant book value of capital stock. These energy intensity distributions are rather flat, with no apparent trend. The vintage class for 1973-1976 shows extreme variation, which is probably a result of the valuation and deflation of the capital stock data for those years. As was found for cement (Section 4.1.3), if capital stock were to be used to define energy intensity, a much more careful treatment of capital stock would be required. At this stage of the project, a strong preference is shown for engineering capacity measures when these external technical data can be obtained and linked to the LRD. For electricity, the regression results show no significant trend. The fossil fuel results do indicate a significant trend.

4.2.4 Energy/Output Tonnage Ratio

For the steel industry, a physical output series (in tons of raw steel poured) was constructed from trade publication data. This series can be used to examine the energy intensity behavior of different vintages. It can be argued that physical output is more closely linked to energy use than deflated shipments in these energy-intensive sectors.

Figure 4.7 shows a striking similarity to Figure 4.5, the plot of capacity-based intensity data. The figures are derived from the same sources, so this similarity may not be surprising. A significant downward trend in electricity use per ton of steel — 0.7% per year — is shown in Table 4.7. An even larger reduction in fossil fuel use per year of installed vintage — 2.9% — is significant as well.

**TABLE 4.5 Regression Results for Steel Industry
Energy/Capacity Ratio**

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0099	560.28549	8309.151497 3.694	-3.933676 -3.445	-0.70
Fossil fuel t-ratio	0.0382	5.15695	289.636616 6.998	-0.144415 6.874	-2.92

**TABLE 4.6 Regression Results for Steel Industry
Energy/Capital Stock Ratio**

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0003	3.52351	-34.538541 -0.578	0.019322 0.637	0.50
Fossil fuel t-ratio	0.0111	0.02284	0.804900 3.748	-0.000397 -3.642	-1.3

**TABLE 4.7 Regression Results for Steel Industry
Energy/Output Tonnage Ratio**

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0091	820.91588	-12578 3.537	-5.968340 -3.306	-0.7
Fossil fuel t-ratio	0.0337	7.58741	427.072716 6.560	-0.212950 -6.443	-2.90

FIGURE 4.5 Plant Energy/Capacity Ratio Vintage Distributions for the Steel Industry
(Source: Table A.9)

FIGURE 4.6 Plant Energy/Capital Stock Ratio Vintage Distributions for the Steel Industry
 (Source: Table A.10)

FIGURE 4.7 Plant Energy/Output Tonnage Ratio Vintage Distributions for the Steel Industry (Source: Table A.11)

4.3 IMPLICATION OF VINTAGE DEFINITIONS

To examine the implications of using either kiln installation or investment-based measures of vintage to analyze energy use in the cement industry, plots of energy intensity based on these measures can be studied. Two alternative investment-based indices and some plots of the energy/output ratios are constructed. Since the data used to construct the two investment-based indices come from different subsamples, two different approaches are needed to compare each of the two investment-based indices with the installation-based measures.

The first set of plots compares the net investment index (VINDEX) to the energy intensities derived from the two kiln installation measures of vintage (Figure 4.8). The sample of cement plants was divided into three categories on the basis of each of the vintage measures: the lower third is the OLD category, the middle third is the MID category, and the top third is the NEW category. There are roughly 30 plants in each category. $VINT_1$ and $VINT$ represent the weighted and unweighted kiln installation measures of vintage, respectively (Section 2). VINDEX represents the net investment measure. The left-hand side of the figure indicates plant electricity and fossil fuel intensities in 1977, based on the different measures of vintage. The right-hand side shows the same intensities in 1987.

The trends shown by the three different measures of vintage in all four plots look very similar. In the cement industry, as plants become newer, electricity intensities rise and fossil fuel intensities fall. Nevertheless, there is some variability. The kiln installation and the investment measures do capture somewhat different aspects of vintage. A study focusing on the performance of kilns of a certain age might rely on kiln installation data, which take into account the specific vintage of installed kilns. A study focusing on the impact of overall investment on energy use might rely on a measure that takes overall investment into account.

The second set of plots (Figure 4.9) uses the fourth measure of vintage, (based on gross investment). Figure 4.9 compares directly with Figure 4.1 (energy/output distributions for the cement industry). These plots show a nearly flat (or slightly rising) trend in mean electricity intensity as vintage becomes more recent. A more perceptible downward trend is seen for fossil fuel. These observations are reflected in the regression results in Table 4.8. Although these results are similar to those found by using other vintage measures, the variation in the vintage classes based on gross investment is larger than those shown in Figure 4.1.

4.4 POLLUTION-ABATEMENT COSTS AND EXPENDITURES FOR THE CEMENT INDUSTRY

The Survey on Pollution Abatement Capital Expenditures is conducted annually by the U.S. Bureau of the Census.¹⁵ The survey samples about 20,000 establishments each

¹⁵ A more detailed discussion can be found in U.S. Bureau of the Census (1991). The discussion in this section summarizes the information from that source.

FIGURE 4.8 Comparison of Plant Energy/Output Ratios on the Basis of Alternative Vintage Definitions for the Cement Industry (Source: Table A.12)

FIGURE 4.9 Energy/Output Distributions on the Basis of a Gross-Investment-Based Vintage Index (VINDEX) for the Cement Industry (Source: Table A.13)

TABLE 4.8 Regression Results for Cement Industry Energy/Output Ratio on the Basis of Gross Investment Vintage (VINDEX^{GROSS})

Energy Type	R ²	Mean Intensity	Regression Coefficient		Vintage Effect (%/yr)
			Intercept	Vintage	
Electricity t-ratio	0.0017	2.547	2.511696 63.235	0.001354 1.343	0.05
Fossil fuel t-ratio	0.0203	0.099	0.10529 54.778	-0.000234 -4.803	-0.23

year. The sample is a subsample of the ASM. The ASM from which the sample is chosen differs depending on the year in question. One purpose of the survey is to find out how much money is spent by the manufacturing sector for pollution abatement in general and for the abatement of particular pollutants (e.g., particulates, nitrogen oxides, carbon monoxide, sulfur oxides, and various toxic wastes). Another purpose is to shed light on how much pollution is actually abated as a result of the various control methods. The data collected by this survey are available for 1979-1986, 1988, and 1989; the survey was not conducted in 1987.

As the name of the survey suggests, the questionnaire asks respondents to provide data on total capital expenditures and operating costs for pollution abatement in a given year. Pollution-abatement capital expenditures (PACE) are broken down into PACE for air, water, and solid wastes. Total PACE for air and total PACE for water are further divided into two categories: PACE for the plant and equipment designed to reduce or eliminate pollutants through end-of-line (EOL) techniques and PACE for the plant and equipment designed to abate the generation of pollutants through changes in the production process (CIPP). Capital expenditures for solid-waste abatement are classified into hazardous and nonhazardous materials. Data on total pollution-abatement operating cost (PAOC) are available for all sample years. For 1983-1989, PAOC data were collected on depreciation, labor, materials, and services. The data from the survey are a rich source of information. The plant-level information about pollution abatement activities opens up many avenues for research.

For the survey years 1979-1986 and 1988, there are pollution-abatement data for 104 plants at various times. Table 4.9 breaks down by year the number of plants surveyed and shows total PACE and PAOC data, deflated with a GNP deflator, for the sample. Table 4.10 shows the percentage of capital expenditures spent on air, water, and solid-waste pollution abatement.

To analyze pollution-abatement expenditures by vintage, the above data are combined with the kiln (capacity) data discussed earlier. This procedure decreases the sample size to 64 plants. Table 4.11 shows the number of plants and total PACE and PAOC data by year for the sample used in the analysis.

TABLE 4.9 Expenditures on Pollution Abatement for Entire Sample for the Cement Industry

Year	No. of Plants	Total PACE (10 ⁶ 1982 \$)	Total PAOC (10 ⁶ 1982 \$)
1979	41	5.9	23.2
1980	36	8.8	19.4
1981	36	16.8	14.8
1982	47	13.6	15.5
1983	36	15.0	16.2
1984	64	8.0	23.2
1985	54	3.0	17.8
1986	56	8.2	21.2
1988	56	3.7	18.6

TABLE 4.10 Percentage Break-down of Pollution-Abatement Capital Expenditures for the Cement Industry

Year	Air	Solid Wastes	Water
1979	85.6	2.3	12.1
1980	87.3	6.3	6.4
1981	94.5	0.9	4.6
1982	97.5	0.7	1.8
1983	70.6	15.2	14.2
1984	95.0	4.1	0.9
1985	79.0	20.4	0.6
1986	95.1	4.2	0.7
1988	79.4	7.4	13.2

These data were used as a basis for determining whether vintage has any effect on pollution control expenditures. The vintage measure that represents the year the newest kiln was installed was the basis for Figures 4.10-4.15. These figures show no clear pattern in pollution control expenditures as a result of plant vintage. Because the data were acquired so recently by CES, there was not enough time to edit the data (e.g., by deleting outliers and imputed data) to enhance the reliability of the results. This situation could explain the lack of pattern in capital expenditures. Another possible explanation is the "lumpy" nature of capital goods. PACE data show this lumpiness. Gray and Shadbegian (1993) found a great deal of fluctuation in plant capital expenditures over time. Some pattern would probably emerge from a more careful analysis of the data set, because of the mandated nature of pollution-abatement capital expenditures. The data need to be understood more fully than is allowed by this graphical analysis. An analysis of the years for which the variation is largest would be a good starting point.

TABLE 4.11 Expenditures on Pollution Abatement for Sample Used for Analysis for the Cement Industry

Year	No. of Plants	Total PACE (10 ⁶ 1982 \$)	Total PAOC (10 ⁶ 1982 \$)
1979	30	4.3	19.4
1980	27	8.0	18.3
1981	26	16.2	12.5
1982	31	12.1	12.5
1983	29	7.9	14.9
1984	47	7.3	19.8
1985	39	2.6	14.8
1986	44	7.9	18.8
1988	43	3.6	7.5

FIGURE 4.10 Plant Pollution-Abatement Capital Expenditure/Output Ratio Vintage Distributions for the Cement Industry (Source: Table A.14)

FIGURE 4.11 Plant Pollution-Abatement-Operating Cost/Output Ratio Vintage Distributions for the Cement Industry (Source: Table A.14)

FIGURE 4.12 Plant Pollution-Abatement Capital Expenditure/Capital Stock Ratio Vintage Distributions for the Cement Industry (Source: Table A.15)

FIGURE 4.13 Plant Pollution-Abatement Operating Cost/Capital Stock Ratio Vintage Distributions for the Cement Industry (Source: Table A.15)

FIGURE 4.14 Plant Pollution-Abatement Capital Expenditure/Capacity Ratio Vintage Distributions for the Cement Industry (Source: Table A.16)

**FIGURE 4.15 Plant Pollution-Abatement Operating Cost/Capacity Ratio
Vintage Distributions for the Cement Industry (Source: Table A.16)**

5 DETAILED MODEL OF VINTAGE EFFECTS IN THE STEEL INDUSTRY

This section examines the steel industry sample in more detail. The heterogeneity of the steel industry is well known, and plots of energy intensity indicate this substantial heterogeneity through their large standard deviations. To allow for a better understanding of how vintage affects energy use, a series of analytic approaches are applied to a homogeneous subset of the steel plants. These analyses allow the trend in technology improvement to be correlated with plant vintage in the only segment of the U.S. steel industry that is growing: electricity-intensive, scrap-based minimills.

The National Energy Accounts reports that steel manufacturers used 3.2 quads¹⁶ of fossil-fuel-based energy during 1970; the use of fossil energy declined to 1.7 quads in 1985. Use of electricity by the steel industry increased from 49.4 billion kWh in 1970 to a maximum of 64.3 billion kWh in 1979 before falling to 51.0 billion kWh in 1988. The increased use of electricity was largely attributable to the closure of many coal-based integrated mills and the introduction of minimills, with their electricity-based furnaces.

A plant that uses scrap in EAFs uses about half as much total energy per ton as a plant that uses ore in blast furnaces-basic oxygen furnaces. The reason is mainly because the energy required to melt steel scrap is much less than that needed to reduce ore to iron (Ross 1987). The changing energy requirements of steel manufacturers also alter the form of environmental pollution. The coke ovens that serve blast furnaces are direct sources of sulfur dioxide (SO₂), nitrogen oxides (NO_x), particulates, and CO₂. Steel-making furnaces, including EAFs, produce fewer pollutants at the plant site.

Steel makers that use EAFs have reduced their electricity intensity. Figure 5.1 (EPRI 1987) traces improvements in electricity consumption in EAFs and shows a chronology of changes in furnace practices between 1965 and 1985. State-of-the-art furnaces have been reducing their energy intensities at the rate of almost 10 kWh/ton of raw steel each year. Because the minimills have become major suppliers of steel, and because many vintages of minimills coexist, the data used to examine the role that vintage plays in determining energy and technical efficiency are disaggregated to create a minimill sample.

Research shows the value of sample disaggregation and supplemental data in understanding vintage effects. Figure 4.4, based on data in the LRD, traces mean electricity intensity in kilowatt-hours per constant dollar value of shipments for the entire steel industry. Mean electricity intensities increase with vintage (i.e., as plants become younger). Because the entire steel industry includes specialty steel producers and integrated producers that use EAFs in addition to fossil-fuel-based furnaces, the sample represented is too heterogeneous to support the claim that electricity intensities decrease for newer plant

¹⁶ One quad = 10¹⁵ Btu.

FIGURE 5.1 Technical Assessment of Steel Manufacturers that Use Electric Arc Furnaces through the Year 2000 (Source: EPRI 1987)

vintages. Figure 5.2 reports mean electricity intensities per ton of steel by vintage for a sample of minimills. This figure should be a more accurate depiction of vintage effects on energy in the minimill subsector, although a clear trend is difficult to discern. The effect of vintage on energy intensity is examined more closely in the next section.

5.1 MINIMILLS IN THE STEEL INDUSTRY

Figure 5.2 draws its data from a sample of steel plants explicitly designed as minimills. Such plants refine carbon steel (usually recycled scrap) in an EAF and pour the steel into a continuous casting machine that produces steel billets or slabs to be rolled into final products. This technological definition of minimill is used to obtain a sample of plants that use different vintages of similar machinery. A number of the steel plants that previous studies classified as minimills were originally built with open-hearth furnaces or with ingot casting. Many of those plants have converted to EAFs and continuous casting. Because such plants were not originally designed with EAFs and continuous casting in mind, their energy use may be higher because of additional transportation and reheating costs incurred in manufacturing the final products. Such plants are not considered here. Specialty steel production is very energy intensive; it produces an extremely high-value product.

FIGURE 5.2 Vintage Distribution of Electricity Intensity for All Steel Minimills (Output: tonnage)

The plants in the minimill sample have a variety of productive capacities. Productive capacity is not used as a screen for selecting minimills. Commentators have offered capacity-based definitions of minimills that have changed over the years. Hogan (1987, p. 9) reports that in early definitions, minimills were limited to annual capacities of 100,000 or fewer tons of raw steel per year. Schmidt and LeHeron (1976, p. 531) include plants with capacities up to 400,000 tons per year; Hogan (1987, p. 11) includes plants with capacities in excess of 1 million tons per year. The smallest surviving integrated steel plants have less capacity than these largest minimills. Because of improvements in EAF technology and operating practices, many plants that once produced less than 400,000 tons of raw steel in a year now produce 750,000 or more tons of raw steel.

Steel minimills use electricity in volumes that Preston (1991, p. 178) equates to the demands of a city. Barnett and Crandall (1986, p. 85) estimate that 80% of a minimill's power is used to operate the EAFs. Steel producers have installed ultra-high-power EAFs and water-cooled furnace walls and roofs that boost output yet preserve the furnace lining from burn-throughs. The industry classifies furnaces in terms of the power they deliver (kilovolt amps delivered per square foot of hearth area). Regular power is up to 160 kVa/ft², high power exceeds 180 kVa/ft², and ultra-high power exceeds 200 kVa/ft² (Ciotti and Pelfrey 1985, p. 24). The use of such high power leads to hot spots in the furnace lining near the electrodes (Lawrence 1985, p. 10). Hot spots can burn through, causing steel to spill and great risk to workers.

5.2 TECHNICAL EFFICIENCY

To understand energy efficiency in minimills, the procedure adopted is to first apply a general technique to assess plant-level differences in productivity (i.e., technical efficiency). Differences in the level of overall productivity or efficiency directly affect energy efficiency. Once the effect of plant productivity is accounted for, the vintage effect on energy intensity can be measured by a statistical model.

The Farrell (1957) efficiency linear programming technique, also known as data envelopment analysis, is used to calculate measures of technical efficiency. The technique uses a linear program to determine the establishments that make up the "best practice production frontier." That frontier, or envelope, approximates the underlying production isoquants. All establishments operating on the frontier have an efficiency rating of one (100% efficient). All other establishments (operating inside the envelope) have efficiency ratings of less than one.

The concept is illustrated by Figure 5.3. Two inputs are considered, K and L. In any year, the most efficient plants are defined as those that use the least input per unit of production. Two such plants, A and B, and similarly efficient plants define the 100%-efficiency isoquant, P_1 , for that year. Plant C, being farther from the origin of the input, is less efficient. The efficiency is simply the ratio of one distance to another: the distance from the origin to the isoquant to the distance from the origin to plant C.

The linear program finds a set of weights that creates a linear combination of the inputs (electricity and all other inputs) that produce a feasible output on the basis of all other establishments in the sample. The program compares the linear combination of inputs with the actual output of an establishment. If potential output, as measured by the linear combination, exceeds actual output, the establishment is inefficient, and the proportion, λ , by which all inputs are scaled to reach the frontier is the efficiency measure. (See Appendix C for a statement of the linear program solved.)

This study uses five input measures and one output measure from the linked database:

- *Capital.* Annual plant-level capacity measured in thousands of short tons of output. (This measure is taken from the Karlson database.)
- *Labor.* Production worker hours at the plant level adjusted to account for nonproduction workers. Specifically, the ratio of total salaries and wages to production worker wages was multiplied by production worker hours to obtain a measure of total labor input. (These measures are derived from the LRD.)
- *Electricity.* Purchases of electricity measured in thousands of kilowatt-hours at the plant level. (This measure is drawn from the LRD.)

FIGURE 5.3 Example of Efficiency Frontier Calculation for Steel Minimills

- *Fuels.* Cost of fuels purchased at the plant level. (This measure is taken from the LRD and deflated by the National Bureau of Economic Research [NBER] four-digit energy deflator.)
- *Materials.* Cost of purchased nonenergy materials adjusted for changes in inventories at the plant level. (This measure is taken from the LRD and deflated by the NBER four-digit SIC nonenergy materials deflator.)
- *Output.* Raw steel in thousands of short tons. (This measure is drawn from the Karlson database.)

The first step in the data analysis was to clean up the data. Although the LRD contains measures of economic activity for all manufacturing establishments in CM years and for a significant portion of manufacturing establishments in non-CM years, some of the data on individual establishments were imputed. In other words, because some companies file unreliable ASM or CM forms or are not required to complete them, the Bureau often uses industry averages to impute responses. Such imputed responses are more likely to reflect the behavior of industry averages than the behavior of an individual establishment. This study examines the relationship between various characteristics of capital and energy consumption at the plant level. The inclusion of imputed data could obscure such relationships. Thus the first step in editing the data from the LRD was to eliminate all imputed records. After imputed records were eliminated, the ratio of each input to each output was examined at the plant level. Extreme values for IO ratios were examined in detail to determine if such values represented unreliable responses.

The linear programming problem for each plant in the sample was run and compared with all other firms for each year. The Andres-Pregibon statistic (Andres 1978), which is

commonly used to detect influential outliers in data envelopment analysis, was employed as a diagnostic tool. Extreme values of the Andrews-Pregibon statistic were examined to determine if they were associated with unreliable responses. The sample size was small enough so that a detailed examination of individual establishment records could be easily undertaken. Thus it can be confidently assumed that the influence of unreliable data was minimized.

Because the LRD is not a balanced panel (i.e., every establishment is not represented every year), the sample was not pooled over years. The technical efficiency score therefore does not incorporate changes in technology over time. The distribution of the means of plant technical efficiency is shown in Figure 5.4. The technical efficiency scores move cyclically. The lowest mean values appear during downturns in the steel business, especially 1976 and 1981-1983.

Technically efficient plants are found to use less energy. Figure 5.5 shows the distribution of plant-level energy output ratios (i.e., energy intensity) for each sample year. The mean energy intensities of the efficient plants are shown as a solid bar on the graph. Because there are too few efficient plants, the Bureau's restrictions prevent reporting data for 1981, 1984, and 1987. The greatest divergence between mean energy intensities and efficient energy intensities appears during the business downturns. Because results suggest that even at the worst points of these downturns, few of the technically inefficient plants close, policymakers should design carbon taxes or other energy-reducing measures with great care. A poorly designed carbon tax that raises costs and leads to reduction of output might also increase energy use, as plants reduce their output and become less technically efficient and less energy efficient.

The best-practice minimills (i.e., those with the highest level of technical efficiency) are more energy efficient than the minimill industry on average in nonrecession years as well. The electricity intensity of best-practice minimills is about 20% lower than the industry's average intensity (Figure 5.5). The role of vintage in determining best practice has not yet been studied.

Energy intensity and efficiency vary significantly over the sample period. Capacity utilization plays a key role in causing this variation. Figure 5.6 shows the distribution of capacity utilization for all plants and the mean for the efficient plants. As a general rule, utilization is much higher for efficient plants. The implication is that any economic policy that reduces capacity utilization among minimills has adverse consequences on energy use and environmental pollution. A stable macroeconomic environment and a combination of pollution control incentives that would lead to quick replacement of the most energy intensive plants would be more likely to reduce energy use and pollution.

As Figures 5.4-5.6 show, changes in energy intensity and technical efficiency appear to be strongly related to capacity utilization. A simple regression model that controls for capacity utilization and then measures the effect of plant vintage is used to assess the effect

FIGURE 5.4 Plant Mean Technical Efficiencies for Steel Minimills

FIGURE 5.5 Plant Mean Energy/Output Ratios for Steel Minimills (Source: Table A.17)

FIGURE 5.6 Plant Mean Capacity Utilization for Steel Minimills (Source: Table A.17)

of plant vintage on energy intensity and technical efficiency. There are two equations, one for technical efficiency and one for energy intensity. Several of the variables in the model are common to both equations. Three capacity utilization terms are used: linear, quadratic, and first difference. The quadratic and first-difference terms capture possible nonlinearities in this relationship. The first-difference term identifies changes in energy intensity and technical efficiency stemming from cyclical increases or decreases in industry activity. The year that the last major furnace upgrade is installed is used to model vintage effects.

The equation for energy intensity includes the technical efficiency score. According to the technical efficiency measure used here, plants with low technical efficiency tend to have a higher energy intensity. This specification creates a recursive system of equations and allows the model user to compute the reduced-form effects of the vintage and utilization terms. The only departure from this strictly triangular form is the inclusion of year dummy variables in the second equation. Because technical efficiency is computed for each year, unless the sample is pooled, the year-to-year scores may not be strictly comparable. To control for this occurrence, the year dummies are used. The equations are as follows:

$$\frac{E}{Q} = \alpha + \beta_E \text{Vintage} + \gamma_{E1} \text{Util} + \gamma_{E2} \text{Util}^2 + \gamma_{E3} \Delta \text{Util} + \tau \text{TECH} \quad (11)$$

and

$$TECH = \sum_{t=72}^{88} \delta_t D_t + \beta_T Vintage + \gamma_{T1} Util + \gamma_{T2} Util^2 + \gamma_{T3} \Delta Util, \quad (12)$$

where the Greek letters are parameters, the variables are defined in the tables below, and each observation is at the plant level for the pooled period 1972-1988. The equations were estimated as a system by using two-stage least squares. The parameter estimates are shown in Tables 5.1 and 5.2.

The regressions suggest that (1) older plants have higher energy intensities and lower technical efficiencies and (2) a higher level of capacity utilization is correlated with greater technical efficiency. Specifically, the sign for the vintage variable is negative in Equation 11, in which older plants have a higher energy intensity, and positive in Equation 12, in which older plants have a lower technical efficiency score. In both equations, lower capacity utilization rates mean less efficient performance. Since the relationship that is estimated is quadratic in the level of utilization, it is easiest to summarize graphically. Figure 5.7 illustrates the direct effects of utilization on energy intensity and technical efficiency. Changes in utilization have a small direct effect on energy intensity when utilization is near full capacity (i.e., more than 80%). When utilization is less than 80%, the increase in energy intensity is significant; the relationship between utilization and efficiency is much more linear. This result is not surprising, given the way efficiency is calculated. The degree of the change in capacity utilization has a significant effect on energy intensity as well. This effect is in addition to those shown in Figure 5.8. For example, if utilization were to fall by 10%, energy intensity would rise 21.6 kWh/ton. A change in utilization has a similar effect on efficiency scores, but it is small and not statistically significant. The signs suggest that (1) energy efficiency improves with economic recovery or with price adjustments that keep minimills operating at full capacity and (2) during downturns, equipment is not always idled in an optimal fashion.

TABLE 5.1 Parameter Estimates for Energy Intensity Equation for Steel Minimills^a

Variable	Definition	Parameter Estimate	t-Statistic
Intercept		11,080	3.0
Vintage	Year that the last furnace was installed	-4.846	-2.6
Util	Capacity utilization	-1049	-2.2
Util ²	Capacity utilization squared	548.2	2.2
ΔUtil	Change in capacity utilization	-216.1	-2.9
TECH	Technical efficiency	-320.9	-1.4

^a $R^2 = 0.26$.

TABLE 5.2 Parameter Estimates for Technical Efficiency Equation for Steel Minimills^a

Variable	Definition	Parameter Estimate	t-Statistic
Intercept		-8.37	-4.7
D ₇₄	1974 dummy	0.010	0.4
D ₇₅	1975 dummy	0.044	1.5
D ₇₆	1976 dummy	-0.061	-1.1
D ₇₇	1977 dummy	-0.036	-0.3
D ₇₈	1978 dummy	-0.106	-2.0
D ₇₉	1979 dummy	-0.039	0.1
D ₈₀	1980 dummy	-0.044	0.2
D ₈₁	1981 dummy	-0.117	-1.6
D ₈₂	1982 dummy	0.032	2.6
D ₈₃	1983 dummy	-0.132	-1.4
D ₈₄	1984 dummy	-0.111	-0.7
D ₈₅	1985 dummy	-0.017	1.8
D ₈₆	1986 dummy	-0.021	1.9
D ₈₇	1987 dummy	-0.073	0.7
D ₈₈	1988 dummy	-0.078	0.7
Vintage	Year that the last furnace was installed	0.004	4.8
Util	Capacity utilization	1.452	8.7
ΔUtil	Change in capacity utilization	0.055	1.3
Util ²	Capacity utilization	-0.521	-4.8

^a R² = 0.67.

The partial and total effect of age and utilization on technical efficiency and energy intensity are computed next. Because technical efficiency depends on age and capacity utilization and because energy intensity depends on age, utilization, and efficiency, the estimates are based on Equations 13-16:

$$\frac{dE/Q}{dUtil} = -1049 + 1096 \times Util - 216 - 321 \times \frac{\partial TECH}{\partial Util}, \quad (13)$$

$$\frac{\partial TECH}{\partial Util} = 1.452 - 1.043 \times Util + 0.0554, \quad (14)$$

FIGURE 5.7 Impact of Utilization on Technical Efficiency and Energy Intensity for Steel Minimills (Source: Table A.17)

$$\frac{\partial TECH}{\partial Vintage} = 0.004295, \quad (15)$$

and

$$\frac{dE/Q}{dVintage} = -4.846408 - 320.917794 \times 0.004295 = -6.2247. \quad (16)$$

Evaluating Equations 13 and 14 at the plant level yields average values for the comparative statistics of utilization effects on energy intensity. The results are shown in Table 5.3. Intensity increases from 5.6 to 9.3 kWh/ton for a percentage point (one-point) decline in utilization. Thus, a one-year increase in plant vintage (i.e., a newer plant) decreases energy intensity by 6.2 kWh/ton.

5.3 SUMMARY OF STEEL MINIMILL RESULTS

The research compares the vintage effects of energy intensity resulting from best practice as defined by engineering studies with the vintage effects of the technology as adopted and operated. These results are in surprising agreement. Once the variation in capacity utilization is accounted for, the energy intensity of new vintages improves 6.2 kWh/ton per year. The average over the 1965 to 1985 period implied by Figure 5.1 is about 10 kWh/ton per year.

TABLE 5.3 Reduced Form Comparative Statistics Evaluated at Annual Sample Means for Steel Minimills

Year	Mean Capacity Utilization	$\frac{\partial Tech}{\partial Util}$	$\frac{dE/Q}{dUtil}$
1972	0.81	0.66	-589.6
1973	0.81	0.66	-589.6
1974	0.80	0.67	-604.2
1975	0.68	0.80	-775.8
1976	0.64	0.84	-832.8
1977	0.70	0.78	-747.1
1978	0.83	0.64	-561.0
1979	0.81	0.66	-589.6
1980	0.71	0.70	-647.0
1981	0.76	0.71	-661.1
1982	0.57	0.91	-933.0
1983	0.62	0.86	-861.2
1984	0.83	0.64	-561.0
1985	0.70	0.78	-747.1
1986	0.74	0.74	-689.8
1987	0.81	0.66	-589.6
1988	0.89	0.58	-475.3
Mean		0.72	-673.8

If only aggregate data had been used, a different inference might have been made. Although the Electric Power Research Institute (EPRI) reports that a state-of-the-art EAF reduces electricity intensity by about 10 kWh/ton per year, the mean electricity intensity of the sample plants rose from 1972 to 1988, and the minimum calculated values stayed roughly the same during those years. The anomaly is the consequence of two effects. First, the sample is aging. The aggregate data do not reveal best practice behavior, since older plants are averaged in with newer ones. Second, the data measure all the electricity used by a steel plant. The average electricity intensity is about 800 kWh/ton of raw steel, with about 550 kWh/ton accounted for by the EAF itself. The electricity used by the EAF represents about 70% of the plant's total use. The remaining 30% reflects the energy that is used in rolling and treating and miscellaneous activities. That use of energy has changed during the sample period. Minimills that used to produce concrete reinforcing bars and similar simple products now produce a wider range of products. Furthermore, these minimills have installed additional labor-saving equipment and implemented additional environmental controls. Electricity intensities in this sample are lower than those reported by the American Iron and Steel Institute in the *Annual Statistical Report* for 1989 for a sample of minimills. The institute claims an electricity intensity of 980 kWh/ton shipped. The lower intensity

indicated in this report is partly explained by the roughly 90% yield of shipped products from raw steel. In addition, this sample may emphasize the simpler part of the product slate produced by minimills.

The research shows that capacity utilization has a strong effect on energy intensity. Substantial electricity savings are possible as a result of short-run increases in output. Because minimills are frequently praised for their competitive behavior and high rates of capacity utilization (Barnett and Crandall 1986, Chapter 2; Adams and Mueller 1990, pp. 78-79), the presence of periods of low utilization suggests that careful testing for the presence of competitive behavior among minimills would prove fruitful.

6 CONCLUSIONS

6.1 RESULTS

By using plant-level data, researchers can make powerful analyses of industrial performance that are not feasible by using aggregate data. Some of the analyses discussed in this report rely on the ability to match plant-level data from the Bureau with external data on plants and technologies to (1) assign vintages, (2) measure plant-level energy intensity and utilization rates, (3) compare the performance of greenfield plants with average industry performance, and (4) define homogeneous subsamples (disaggregated below the four-digit SIC level). Specific conclusions about the steel and cement industries and some general conclusions about future avenues of research allowed by the LRD and linked databases are described here.

An important purpose of the research described here is to explore the concept of vintage. In Sections 1 and 4, different concepts of vintage (i.e., those based on the date of installation of major facilities and those based on investment data) are found to generate consistent results. Indeed, quantitative representations of vintage appear to have much less variability than do the representations of production that are used in determining energy and pollution intensities.

The study of relative utilization of production capacity across vintages described in Section 2 shows that during economic downturns, the manufacturing industry tends to continue to use plants of many different vintages. Thus, when determining which facilities should curtail production, manufacturers evidently do not base their decisions on simple vintage considerations but are strongly influenced by other factors. For example, marketing considerations related to location, product quality, or knowledge of customers might outweigh simply defined energy cost differences.

The study of how energy intensities in the cement and steel industries depend on vintage is discussed in Section 4. (Table 6.1 summarizes the rate at which energy intensities change.) Only a small degree of plant-level variation in energy intensity is explained by vintage alone. However, statistically significant trends occur in both the cement and steel industries. These results strongly complement aggregate analyses. For example, aggregate fossil fuel intensity in the cement industry fell about 3% per year from the early 1970s to 1985 (Bock et al. 1992, Figure 7). A substantial part of this decline is associated with vintage: Fossil fuel intensity in the cement industry is estimated to decline 1-2% per year of plant vintage, and fossil fuel intensity in the steel industry is estimated to decline 1.3-3.0% per year of vintage. Results on the effect of vintage on electricity intensity in the steel industry are mixed. Therefore, a closer examination is made of the more electricity intensive, growing segment of the steel industry — the minimill segment.

Results of the study of efficiency reported on in Section 5 indicate that the potential for determining best practice in a homogeneous subsector like steel minimills is excellent.

TABLE 6.1 Summary of Annual Vintage Rates of Change (%) in Energy Intensity Ratios for the Cement and Steel Industries

Industry	Energy Type	Energy Use Divided by			
		Value of Shipments	Production Capacity	Capital Stock	Tons
Cement	Electricity	0.60	0.006 ^a	-0.24 ^a	NA ^b
	Fossil fuel	-0.99	-1.70	-1.92	NA
Steel	Electricity	2.26	-0.70	0.05 ^a	-0.70
	Fossil fuel	-0.26 ^a	-2.92	-1.30	-2.90

^a Not significant at a 5% confidence level.

^b Not applicable.

The study relies on the creation of a homogeneous subsector from a heterogeneous sample of plants at the four-digit SIC level and on cross-sectional analysis (a comparison of plants across the country at a fixed time). Both of these capabilities depend on access to plant-level data. The study reveals that in the late 1980s, efficient minimills used about 20% less electricity (measured in kilowatt-hours per ton) than the average amount used by all minimills. The vintage component of this improvement in electricity use is estimated to be 6.2 kWh/ton per year. This estimate agrees with engineering studies on electric arc furnaces and suggests that these data could be used to make high-quality estimates of vintage effects for other industries as well.

6.2 SAMPLE POLICY APPLICATIONS

Does the old age of facilities in an energy-intensive industry that is growing slowly or declining constitute a problem for the United States in terms of improving its industrial competitiveness or environmental quality? Before this question can be answered, several other important questions need to be addressed:

- What are the performance characteristics of older facilities in terms of technical efficiency, energy intensity, and emissions?
- What share of production is represented by older facilities?
- What are the manufacturing sector's practices in terms of retiring or rebuilding old facilities?

For example, consider the cement industry. In 1987, the fraction of plants in which the newest kiln was more than 20 years old was about one-third of total capacity. This older capacity was used about as much as newer capacity. The LRD indicates that the fossil fuel

intensity of older cement plants is about 22% higher than the intensity of newer plants, built in the period 1977-1987. There are 30 older plants in the sample. Thus, from these data, broad information on regional distribution could be generated if needed. The conclusion is that plant-level data can be used to delineate an industry's general structure, and such information would be needed to evaluate a potential policy that might lead to the retirement of plants.

An important need of research and development (R&D) program managers is an estimate of the rates at which technologies under development will be adopted (assuming certain development goals are achieved). The markets for many new industrial technologies are sensitive to the rate of creation of new production facilities. A forecast of the creation of new facilities for a specific industry or product would be useful for projecting markets for new technology; these projections could be used in planning and evaluating R&D programs and other government technology programs.

One type of information from the LRD (combined with trade association data) that is relevant to R&D needs is the historical rate at which capacity has been created at new facilities. In Figure 6.1, the fraction of total capacity built within any specified time is shown for the cement and steel industries. Here age is defined as the difference between the observation year (1987) and the date of the last major facility change (i.e., its vintage). Figure 6.1 shows that if capacity additions and retirements occur at the same rate as they have in the recent past, in five years after a base year (when new process technology becomes available), almost 20% of capacity in these industries would be at plants with major equipment installed after that base year. After 10 years, one-third of the capacity would be at such new plants.

Figure 6.2 illustrates a conclusion that can be reached by examining capacity and energy intensity distributions by vintage. The plot shows the decline in average energy intensity (fossil fuel use per unit of capacity) that would occur in the cement and steel industries if the oldest capacity were retired and replaced with capacity exhibiting the energy intensity of the newest vintage. For the cement industry, the first large gain occurs after the first 20-25% of capacity is replaced. This gain represents the replacement of plants 25 years old or older (see Figure 6.1). Thereafter, the improvement is roughly linear. For the steel industry, the results appear to be more dramatic, but they should be carefully interpreted. Dramatic improvement occurs as the oldest half of the industry is replaced; gains are modest thereafter. However, the newest plants are virtually all scrap-based minimills, which cannot produce the same steel products as the older ore-based and coke-based mills. If the transition shown in Figure 6.2 were to occur, the quality of scrap-based steel would have to improve dramatically or higher-quality steels would have to be imported.

Another challenge to policy analysts and R&D program managers is how to analyze energy-related developments in industries complicated by changes in product composition. For example, the cement manufacturing industry, being homogeneous, is relatively easy to analyze. The steel manufacturing industry, on the other hand, is not homogeneous, and the

FIGURE 6.1 Share of Production Capacity of Plants Younger Than a Given Age in 1987 for the Cement and Steel Industries

FIGURE 6.2 Impact of Retirement of Old Capacity on Fossil Fuel Use per Unit of Capacity for the Cement and Steel Industries

different subsectors have sharply different energy characteristics. The integrated sector is highly fossil fuel intensive; the specialty sector is highly electricity intensive on a tonnage basis; and the minimill sector is moderately electricity intensive and not fossil fuel intensive. Thus, the interpretation of aggregate energy trends in the steel industry is highly uncertain.

By combining plant-level data from the LRD and external sources, one can construct a representative subsector of a nonhomogeneous industry. This procedure is used to create a data set for the minimill sector that enables an examination of energy trends with respect to vintage and other variables. This approach may not be practical in all cases. For example, the integrated steel industry has very few mills, so the extraction of data for this subsector would be restricted by the Bureau's disclosure rules. Other industries, such as the pulp and paper industry and some sectors of the chemical industry, could be disaggregated in the same way.

6.3 FUTURE ENERGY ANALYSIS WITH THE LONGITUDINAL RESEARCH DATABASE

This report explores the characteristics of energy consumption and vintage in six manufacturing industries. Emphasis is on the steel and cement industries. One of the main conclusions is that the LRD data are much more useful when they are combined with other external data. Many of the results described here are derived from plant-level data from the LRD combined with external data on major production facilities. The latter data are used to define vintage as used in this report (i.e., the year of most recent installation of a major item of equipment at the plant).

A much more powerful database for energy and environmental analysis could be created at the CES. The Bureau's Current Industrial Report (CIR) database could provide information on plant-level physical production, replacing the possibly unreliable data on value of shipments in several bulk materials industries. Additional work done by the Bureau, U.S. Environmental Protection Agency, and U.S. Department of Energy on environmental databases — Pollution Abatement Capital Expenditures (PACE), Toxic Release Inventory (TRI), National Acid Precipitation Assessment Program (NAPAP), and Aerometric Information Retrieval System (AIRS) — would enable emission estimates to be integrated into plant-level analyses. Any of several firm-level financial databases would enable interpretation of technical efficiency (Section 5.2) in terms of firms' financial characteristics. The plant-level identification code in the LRD enables the identification of firms in any year.

Public dissemination of all work at the CES is constrained by disclosure rules that protect information about particular plants, small sets of plants, and firms. Although the CES is helpful and encouraging to researchers, there is still a need to develop analyses that are effective despite the disclosure rules. Inappropriate averaging obscures the underlying behavior that is the subject of interest. Statistical measures that would be better at revealing behavior while meeting disclosure requirements need to be discovered. This report constitutes another step in this ongoing process.

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APPENDIX A:

RAW DATA DEVELOPED IN THIS STUDY

TABLE A.1 Vintage Capacity Distributions and Vintage Relative Capacity Utilization Distributions for Cement Plants

Vintage	Capacity Share (see Figure 2.1)			Relative Utilization (see Figure 2.6)		
	1977	1982	1987	1977	1982	1987
47-49	0.0146		0.0141	1.2447		1.0379
50-52	0.0250	0.0146	0.0034	1.2622	0.4097	1.1006
54-56	0.0697	0.0131	0.0232	1.2771	0.9820	0.5615
57-59	0.1232	0.0511	0.0814	1.0004	0.9056	1.0734
60-62	0.0920	0.0709	0.0989	1.1510	1.5021	1.3173
63-65	0.1018	0.0419	0.0365	1.1404	1.0842	0.6336
66-68	0.0836	0.1087	0.0923	0.9560	0.8905	1.1574
69-71	0.1235	0.1009	0.0959	0.9136	0.7501	0.9710
72-74	0.1583	0.1699	0.1652	0.9340	1.4611	0.9446
75-77	0.2085	0.1817	0.1406	0.8424	0.7290	1.0206
78-80		0.0193	0.0697		1.9342	0.9633
81-84		0.2279	0.1788		0.8447	0.9014

TABLE A.2 Vintage Capital Stock Distributions and Vintage Relative Capital Stock Utilization Distributions for Cement Plants

Vintage	Capital Stock Share (see Figure 2.2)			Relative Utilization (see Figure 2.7)		
	1977	1982	1987	1977	1982	1987
47-49	0.0120	0.0112		1.5206	1.3045	
50-52	0.0239	0.0015	0.0061	1.3181	2.4169	0.9767
54-56	0.0470	0.0101	0.0069	1.8933	1.2906	1.8544
57-59	0.0994	0.0546	0.0335	1.2402	1.6007	1.3808
60-62	0.0999	0.0794	0.0712	1.0595	1.6340	1.4957
63-65	0.0978	0.0291	0.0397	1.1878	0.7953	1.1456
66-68	0.0870	0.0836	0.0918	0.9186	1.2798	1.0545
69-71	0.1219	0.1005	0.0830	0.9256	0.9276	0.9118
72-74	0.1443	0.1389	0.1344	1.0245	1.1239	1.8478
75-77	0.2670	0.1307	0.1593	0.6578	1.0984	0.8317
78-80		0.1041	0.0236		0.6458	1.5770
81-84		0.2563	0.3505		0.6292	0.5492

TABLE A.3 Vintage Capacity Distributions and Vintage Relative Capacity Utilization Distributions for Steel Plants

Vintage	Capacity Share (see Figure 2.4)				Relative Utilization (see Figure 2.8)			
	1972	1977	1982	1987	1972	1977	1982	1987
52-55	0.0089	0.006	0.0045	0.0013	1.0193	0.9814	0.8074	1.1208
56-60	0.0291	0.0202	0.016	0.0175	0.8894	0.9772	0.8978	1.0396
61-64	0.0302	0.027	0.0168	0.012	0.959	0.7731	1.0589	0.9266
65-68	0.3106	0.1983	0.1354	0.147	0.9475	0.964	1.1274	1.0107
69-72	0.6212	0.3462	0.3239	0.3165	1.0332	1.0651	1.1138	1.0805
73-76		0.3727	0.3317	0.2136		0.9901	0.8883	0.9606
77-80		0.0296	0.0987	0.1015		0.8304	0.9813	1.0393
81-84			0.0728	0.0952			0.8123	0.8778
85-88				0.0955				0.8854

TABLE A.4 Vintage Capital Stock Distributions and Vintage Relative Capital Stock Utilization Distributions for Steel Plants

Vintage	Capacity Share (see Figure 2.5)				Relative Utilization (see Figure 2.9)			
	1972	1977	1982	1987	1972	1977	1982	1987
52-55	0.0070	0.0050	0.0040	0.0020	1.6710	1.4340	1.5260	1.2970
56-60	0.0360	0.0220	0.0060	0.0050	2.3150	2.2400	1.6240	2.3030
61-64	0.0310	0.0260	0.0210	0.0140	1.8350	1.5770	1.7980	1.9000
65-68	0.2110	0.1630	0.1380	0.1160	1.3020	1.1230	1.2520	1.2170
69-72	0.7150	0.4280	0.3820	0.4040	0.8030	0.7780	0.8220	0.8060
73-76		0.3300	0.3130	0.2040		1.0960	0.9710	0.9950
77-80		0.0260	0.0600	0.0720		0.9620	1.3290	1.3830
81-84			0.0750	0.0930			0.9990	0.9910
85-88				0.0900				1.0890

TABLE A.5 Plant Energy/Output Ratio Vintage Distributions for the Cement Industry (see Figure 4.1)

Vintage	Electricity/Output Ratio		Fuel/Output Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
47-49	W ^a		W	
50-52	2.007	0.592	0.115	0.041
54-56	2.238	0.924	0.114	0.044
57-59	2.555	0.766	0.104	0.050
60-62	2.286	0.968	0.093	0.040
63-65	2.412	0.914	0.120	0.044
66-68	2.818	0.789	0.102	0.045
69-71	2.885	0.818	0.088	0.047
72-74	2.597	0.800	0.102	0.042
75-77	2.735	1.001	0.088	0.043
78-80	3.106	1.041	0.086	0.032
81-84	2.657	0.742	0.067	0.030

^a W = withheld because of the Bureau's disclosure rules.

TABLE A.6 Plant Energy/Capacity Ratio Vintage Distributions for the Cement Industry (see Figure 4.2)

Vintage	Electricity/Capacity Ratio		Fuel/Capacity Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
47-49	W ^a		W	
50-52	100.3	44.65	5.969	3.284
54-56	105.3	40.10	5.603	2.456
57-59	112.5	34.29	4.668	2.414
60-62	123.4	53.23	5.216	3.006
63-65	112.9	32.86	5.919	2.572
66-68	120.8	28.61	4.556	2.658
69-71	124.7	27.03	3.911	2.228
72-74	115.3	31.66	4.601	1.985
75-77	105.2	46.02	3.488	2.026
78-80	142.8	67.41	4.096	2.523
81-84	100.3	31.31	2.502	0.933

^a W = withheld because of the Bureau's disclosure rules.

TABLE A.7 Plant Energy/Capital Stock Ratio Vintage Distributions for the Cement Industry (see Figure 4.3)

Vintage	Electricity/Capital Stock Ratio		Fuel/Capital Stock Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
47-49	W ^a		W	
50-52	3.606	1.908	0.2087	0.1147
54-56	3.631	2.552	0.1792	0.1121
57-59	4.616	3.583	0.1830	0.1592
60-62	4.364	3.897	0.1686	0.1376
63-65	3.258	1.878	0.1586	0.0740
66-68	4.345	3.333	0.1366	0.0792
69-71	3.478	1.667	0.1044	0.0642
72-74	3.502	1.387	0.1420	0.0848
75-77	3.188	2.806	0.0957	0.0608
78-80	3.957	2.970	0.1165	0.1068
81-84	2.961	4.013	0.0776	0.1051

^a W = withheld because of the Bureau's disclosure rules.

TABLE A.8 Plant Energy/Output Ratio Vintage Distributions for the Steel Industry (see Figure 4.4)

Vintage	Electricity/Output Ratio		Fuel/Output Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
52-55	768.9	171.8	8.010	5.102
56-60	954.0	599.0	8.968	9.447
61-64	1218.1	663.1	13.637	16.966
65-68	835.3	412.4	8.507	9.798
69-72	805.8	586.3	9.342	10.973
73-76	664.0	448.2	5.293	7.815
77-80	661.5	279.9	4.032	4.481
81-84	1060.5	867.8	5.034	7.660
85-88	670.4	267.1	2.361	1.651

**TABLE A.9 Plant Energy/Capacity Ratio Vintage
Distributions for the Steel Industry (see Figure 4.5)**

Vintage	Electricity/Capacity Ratio		Fuel/Capacity Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
52-55	536.9	122.6	5.622	3.753
56-60	629.3	368.6	5.854	5.971
61-64	747.9	322.1	7.981	7.086
65-68	589.4	261.7	5.878	6.577
69-72	569.5	443.7	6.939	8.421
73-76	469.4	305.8	3.659	5.075
77-80	473.3	206.6	2.644	2.607
81-84	646.1	482.8	2.980	4.250
85-88	460.8	196.8	1.582	1.065

**TABLE A.10 Plant Energy/Capital Stock Ratio Vintage
Distributions for the Steel Industry (see Figure 4.6)**

Vintage	Electricity/Capital Stock Ratio		Fuel/Capital Stock Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
52-55	2.853	1.920	0.025	0.013
56-60	4.620	3.315	0.029	0.017
61-64	2.587	1.794	0.022	0.016
65-68	3.160	2.181	0.024	0.014
69-72	2.534	1.560	0.029	0.041
73-76	4.677	17.479	0.021	0.049
77-80	3.775	2.666	0.019	0.023
81-84	3.411	2.616	0.009	0.006
85-88	2.608	1.790	0.010	0.016

TABLE A.11 Plant Energy/Output Tonnage Ratio Vintage Distributions for the Steel Industry (see Figure 4.7)

Vintage	Electricity/Output Tonnage Ratio (kWh used per ton of steel)		Fuel/Output Tonnage Ratio	
	Mean	Standard Deviation	Mean	Standard Deviation
52-55	769	172	8.01	5.10
56-60	954	599	8.97	9.45
61-64	1,218	663	13.64	16.97
65-68	835	412	8.51	9.80
69-72	806	586	9.34	10.97
73-76	664	448	5.29	7.82
77-80	661	280	4.03	4.48
81-84	1,060	868	5.03	7.66
85-88	670	267	2.36	1.65

TABLE A.12 Comparison of Plant Energy/Output Ratios on the Basis of Alternative Vintage Definitions for the Cement Industry (see Figure 4.8)

VINT ₁	Year	Electricity Output Ratio	Fuel Output Ratio
Old	77	1.99358	0.12208
Mid	77	2.51872	0.11891
New	77	2.65199	0.11947
Old	82	2.27311	0.09245
Mid	82	2.42353	0.09267
New	82	2.6346	0.08132
Old	87	2.7857	0.0762
Mid	87	2.95884	0.07997
New	87	3.1121	0.06618

TABLE A.13 Energy/Output Distributions on the Basis of a Gross-Investment-Based Vintage Index (VINDEX) for the Cement Industry (see Figure 4.9)

VINDEX	Electricity		Fossil Fuel	
	Mean	Standard Deviation	Mean	Standard Deviation
0-9	2.4798	0.7632	0.1209	0.0455
10-19	2.4165	0.8145	0.1031	0.0469
20-29	2.6379	1.2459	0.0924	0.0489
30-39	2.5603	1.0553	0.0885	0.0422
40-49	2.6003	0.8982	0.0941	0.0424
50-59	2.6474	0.7797	0.0865	0.0352
60-80	2.7121	0.7602	0.0684	0.0254

TABLE A.14 Plant Pollution-Abatement Capital Expenditure/Output Ratio Vintage Distributions and Plant Pollution-Abatement Operating Cost/Output Ratio Vintage Distributions for the Cement Industry

Vintage	Capital Expenditure/ Output Ratio (see Figure 4.10)		Operating Cost/ Output Ratio (see Figure 4.11)	
	Mean	Standard Deviation	Mean	Standard Deviation
47-49	W ^a		W	
50-52	W		W	
54-56	W		W	
57-59	0.0018	0.0037	0.0099	0.0078
60-62	0.0054	0.0136	0.0139	0.0099
63-65	0.0058	0.0118	0.0083	0.0059
66-68	0.0039	0.0062	0.0095	0.0056
69-71	0.0043	0.0077	0.0086	0.0074
72-74	0.0023	0.0060	0.0073	0.0042
75-77	0.0016	0.0036	0.0125	0.0053
78-80	W		W	
81-84	0.0165	0.0353	0.0152	0.0115

^a W = withheld because of the Bureau's disclosure rules.

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**TABLE A.15 Plant Pollution-Abatement Capital Expenditure/
Capital Stock Ratio Vintage Distributions and Plant Pollution-
Abatement Operating Cost/Capital Stock Ratio Vintage
Distributions for the Cement Industry**

Vintage	Capital Expenditure/ Capital Stock Ratio (see Figure 4.12)		Operating Cost/Capital Stock Ratio (see Figure 4.13)	
	Mean	Standard Deviation	Mean	Standard Deviation
47-49	W ^a		W	
50-52	W		W	
54-56	W		W	
57-59	0.0028	0.0056	0.0206	0.0161
60-62	0.0104	0.0228	0.0282	0.0209
63-65	0.0077	0.0108	0.0136	0.0100
66-68	0.0059	0.0086	0.0157	0.0097
69-71	0.0055	0.0090	0.0107	0.0084
72-74	0.0059	0.0194	0.0126	0.0067
75-77	0.0022	0.0044	0.0276	0.0665
78-80	W		W	
81-84	0.0105	0.0217	0.0116	0.0118

^a W = withheld because of the Bureau's disclosure rules.

**TABLE A.16 Plant Pollution-Abatement Capital Expenditure/
Capacity Ratio Vintage Distributions and Plant Pollution-
Abatement Operating Cost/Capacity Ratio Vintage Distributions for
the Cement Industry**

Vintage	Capital Expenditure/ Capacity Ratio (see Figure 4.14)		Operating Cost/ Capacity Ratio (see Figure 4.15)	
	Mean	Standard Deviation	Mean	Standard Deviation
47-49	W ^a		W	
50-52	W		W	
54-56	W		W	
57-59	0.0787	0.1500	0.4939	0.4146
60-62	0.3398	0.9606	0.7671	0.5610
63-65	0.3087	0.6070	0.4512	0.3533
66-68	0.1641	0.2704	0.3988	0.2685
69-71	0.1911	0.3299	0.3555	0.3034
72-74	0.1458	0.4360	0.3310	0.1960
75-77	0.0593	0.1275	0.4747	0.2545
78-80	W		W	
81-84	0.5306	1.0331	0.5257	0.3468

^a W = withheld because of the Bureau's disclosure rules.

TABLE A.17 Plant Mean Technical Efficiency, Plant Mean Capacity Utilization, and Plant Mean Energy/Output Ratios for Steel Minimills

Year	Mean Technical Efficiency (%) (see Figure 5.7)	Mean Capacity Utilization (%) (see Figure 5.6)		Mean Energy/Output Ratio (see Figure 5.5)	
		All Plants	Best Practice	All Plants	Best Practice
1972	90	81	79	661	604.036
1973	93	81	77	703	585
1974	91	80	88	744	682
1975	88	68	71	745	570.95
1976	76	64	70	813	471.92
1977	85	70	83	730	615.29
1978	85	83	90	690	555.489
1979	90	81	85	725	607.399
1980	86	77	85	761	604.823
1981	79	76	W ^a	782	W
1982	79	57	64	889	628.777
1983	66	62	95	825	447.188
1984	82	83	W	710	W
1985	83	70	87	794	622.856
1986	87	74	83	809	643
1987	86	81	W	805	W
1988	90	89	97	749	613

^a W = withheld because of the Bureau's disclosure rules.

APPENDIX B:
METHOD FOR CONSTRUCTING THE
NET-CAPITAL-INVESTMENT-BASED
VINTAGE INDEX FROM SECTION 2

$$\text{VININDEX}_t = \frac{\Delta K_1}{K_t} \times i_1 + \frac{\Delta K_2}{K_t} \times i_2 + \dots + \frac{\Delta K_t}{K_t} \times i_t$$

where:

$$\begin{aligned} \Delta K_t &= \Delta \text{DBV between current and previous Census of Manufactures (CM),} \\ &= 0 \text{ if } \Delta \text{DBV} = 0; \end{aligned}$$

$$\Delta \text{DBV} = \text{change in deflated book value of assets (building and machinery);}$$

$$K_t = \sum_s \Delta K_{t-s},$$

$$= \text{sum of } \Delta \text{DBV for current and all past CMs; and}$$

$$i = 1 \text{ for } \Delta \text{DBV in 1963, 2 for } \Delta \text{DBV in 1967, 3 for } \Delta \text{DBV in 1972, 4 for } \Delta \text{DBV in 1977, 5 for } \Delta \text{DBV in 1982, and 6 for } \Delta \text{DBV in 1987.}$$

For example, for a plant coming into existence in 1977 with $\text{DBV}_{77} = 100$, $\text{DBV}_{82} = 150$, and $\text{DBV}_{87} = 200$:

$$\Delta K_{77} = 100 - 0 = 100 K_{77} = 100 i = 4,$$

$$\Delta K_{82} = 150 - 100 = 50 K_{82} = 150 i = 5,$$

$$\Delta K_{87} = 200 - 150 = 50 K_{87} = 200 i = 6,$$

$$\text{VININDEX}_{77} = \frac{100}{100} \times 4 = 4,$$

$$\text{VININDEX}_{82} = \frac{50}{150} \times 5 + \frac{100}{150} \times 4 = 4.3, \text{ and}$$

$$\text{VININDEX}_{87} = \frac{50}{200} \times 6 + \frac{50}{200} \times 5 + \frac{100}{200} \times 4 = 4.75.$$

APPENDIX C:

LINEAR PROGRAMMING PROBLEM

To implement the Farrell efficiency approach, the following linear programming problem is solved (Färe et al. 1985):

$$\begin{aligned}
 &\text{Min } \lambda \\
 &\text{Subject to} \\
 &Z \cdot M \geq u^0 \\
 &Z \cdot N \geq \lambda x^0 \\
 &Z \in R_t^k \\
 &\lambda \in R_t
 \end{aligned}$$

where:

x^0 = observed input vector,

u^0 = observed output,

M and N = matrices of inputs and outputs for the entire sample, and

z = an activity vector.

The first constraint requires the linear combination of other plants' inputs to lie in the input requirement set for output u^0 . The second constraint requires that actual output not exceed potential output on the frontier. The third constraint requires each firm to receive a non-negative weight in any linear combination of inputs or outputs.

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