INDUSTRIAL ENERGY INTENSITY: MODELING DECISION-MAKING

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Our focus is investment in production-process technologies by the energy-intensive industries (and in energy-related technologies in other capital-intensive industries). Government plays important roles here, protecting the environment by regulating production processes, supporting research and development and pursuing other technology policies to enhance industry-wide competitiveness (Nelson 1982), protecting to some degree investments in capital-intensive facilities, and so on. The research we discuss is aimed at understanding decision making on production-process investments in order to improve policy making aimed at enhancing the competitiveness of domestic industries. This paper is in two parts: the first presents a broad *picture* of what we think has been learned so far; the second is about our present studies on the adoption of new technology.

Policy analysts often want to know which technologies will reduce production costs and energy intensities in industry. They also like to know what capital costs and operating savings would be associated with each advanced technology. We are skeptical about this technological specificity, because the specificity doesn't fit the variety of industrial activity. There are two aspects of this variety: one is physical and the other largely behavioral. The physical dimension is simply that even within a major industry sector products, processes and plants differ widely.

- There are many different product-sectors of substantial significance for industrial energy analysis. For example, distinguishing between simple carbon steel products for construction and products like sheet for automotive body panels.
- For each such product category there also may be important variations in the input materials and underlying processes.
- Physical differences between existing plants can also imply major differences in retrofit or replacement opportunities.

In addition, there are also important behavioral differences. In particular, investment decision making can vary from firm to firm and plant to plant. Aspects of this decision making are the main subject of this note.

These complications do not mean that powerful analysis is impractical or of little value. In our view, what is indicated is that industrial energy analysis needs to take interplant variations into account without resorting to the aforementioned level of technological specificity. Improved information about what actually happens in industry is needed, appropriate questions need to be asked, and inappropriate ones need to be avoided. One can hope to learn what kinds of technology are adopted, what impacts they are likely to have on productivity and energy intensity, and what factors encourage or discourage adoption.

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BACKGROUND

Investment decision making on production-process technology

The goal for a production process is often described in terms of minimization of total costs. Although this is a powerful concept, it is a complex one. Consider some important examples.

Product markets are complex: reliability of production, product quality, and product innovation, are usually critical for the continued participation of the firm in its respective market. Major investments whose purpose is competing in product-quality areas are made even by firms in serious financial difficulty. A good example of this is the integrated steel industry, which, despite severe constraints, has invested in major new facilities to improve and modernize their products. To cut costs, *as such*, however, the industry usually restricted itself to low-capital-cost techniques. One can infer from observations like this that quality improvements are more important that cost reduction, at some level of quality, in many product markets.

Decision making at different levels within a large firm presents complex issues which affect the propensity to invest and the kinds of technology that are favored. Top management at a firm defines a firm's financial strategies. Today's financial markets seem to undervalue investment in existing facilities; this usually induces management to restrict raising capital for those investments. These funds must usually come from cash flow. The competition for this cash, and the scarcity of top management time, lead to capital rationing in many, probably most, firms. With capital rationing, funds available at the plants and divisions is highly restricted, with the result that small and medium scale projects face high hurdle rates (Ross 1987). Very small projects are often not so restricted. For the projects that are undertaken, it becomes important that a variety of players be satisfied. Multipurpose projects, that, for example, increase the reliability of production, enhance environmental compliance, or improve product uniformity or quality are likely to be favored in addition to reducing costs in a narrow static sense.

Capital rationing does not necessarily affect investment decisions by top management. They can always decide to go to external markets to raise investment funds. However, they will typically do so only for major strategic projects which excite the interest of stockholders and the investment community, not for cost reduction by modernizing or replacing existing facilities. Instead the investments they choose tend to be externally visible and strategic in nature, involving new products, or markets in a new region.

A related consequence of capital rationing is that certain kinds of potential cost reduction are frequently not even considered. Because funding of a class of projects is unlikely, the opportunities may not be known; the appropriate people may be too busy with other responsibilities to learn about them, unless they have personal interest in the area. Energy efficiency often falls in this category, although not in the most energy-intensive businesses. The important concept here is a *threshold* for attention. Although it may seem in theory that reducing energy costs would be important to overall profitability, energy-efficiency projects are often below the threshold of attention in moderately energy-intensive industries. This was not so in the decade 1974-84.

Capital rationing may be a appropriate tool for top management to control for risk at the plant level not merely a constraint. For this to be the case the capital budget would need to be very dynamic, rather than static. Ellsworth (1983) presents evidence that this capital rationing subordinates financial policy to good corporate policy and that it more likely reflects the management's inability to appropriately delegate authority.

The relationship of historical production processes, as they depend on energy prices, to processes predicated on cost-minimization e.g., conservation supply curves CSCs from general engineering analysis, is subtle. When it comes to adoption of particular technologies in a real-world production process, the total cost mentioned above is just an abstraction. If we analyze projects using directly accounted costs, as is customary, then cost minimization may be far from the decision makerís concerns.

Indeed, decision makers are often uninterested in production-process improvements which "merely" reduce costs (unless the cost reductions are large). The reason for this apparent contradiction is that factors which are not accounted as costs attributable to a decision are often important. The result is that cost minimization, where the costs are restricted to those normally accounted for in an investment decision, is inhibited. The inhibitions we have identified (capital rationing for all but large strategic projects, and a threshold for attention that applies to factors which are relatively small) are important for many energy-efficiency investments, which are often small to medium size investments and are not of strategic significance for the firm. Critical questions for analysts are:

- To what extent are these inhibitions inherent?
- Can they be overcome with better management?

Our analytical approach, discussed below, is beginning to address such questions. We ask: What can we learn from the "best practice" plants?

Decisions about adoption of new technology are also critical to energy-efficiency policy making. The dissonance between the concepts of simple cost minimization and total cost minimization, represented by observed behavior just discussed, also characterizes decisions about new technology. New technology may be adopted very slowly by some firms and at many plants, even if simple cost minimization for a typical plant suggests that it should be rapidly adopted. We consider a model involving three reasons for delay:

- Existing production-process facilities are of different vintages and regional markets experience different growth rates; so the motivations to add, replace or modify plant capacity vary.
- Uncertainty about the performance of the new technology varies, uncertainty which depends on the technological sophistication of the firm and plant.
- Managementís have differing degrees of risk aversion, with the degree depending on factors like a firm's financial position and management's long-term goals.

These factors can be combined to extend a simple theoretical model (Howarth, 1993) of the decision whether or not to adopt a new fundamental technology (Boyd, 1993).

Uncertainty and risk aversion have been observed to vary widely (CITE?). Some decision makers find it desirable to gain early experience with new technologies, while others find it desirable to wait until a great deal of experience has accumulated elsewhere. If the level of uncertainty perceived by decision makers and their risk aversion vary across an industry, then one will observe a distribution of technologies in place. If a new technology represents progress, some of these adoptions should be representative of best practice. Critical questions are:

- Do best-practice plants tend to be innovators, i.e. initial adopters?
- Is "energy technology" different from technologies which focus on other production inputs?

Our approach focuses on the variety of achievements by existing plants including the choice and timing of adoption of technologies.

Approach

The basic approach is economic analysis of historical data. We have used, or are beginning to use, a variety of detailed sources, especially Census plant-level economic, energy and environmental data, and data on technology adoption from trade associations, trade journals and the Manufacturing Energy Consumption Survey. The information that can be made public for the work with the Census plant-level data is restricted to standard Census confidentiality clearance procedures. In the future, we plan to merge such data sets with financial data for public firms. We also hope to make use of Energy Analysis and Diagnostic Center data on decision making for small projects.

These data can be used to determine historical CSCs (as contrasted with those from general engineering analysis). A simple example of this approach is the historical analysis of national average energy intensities and energy prices to establish parameters for the LIEF model (Ross et al 1992). Let us dwell for a moment on this. "Engineering" CSCs have been created by compiling a purportedly complete list of improved technologies with, hopefully, some information on their existing level of adoption. For idealized plants representing broad sectors, the analyst then introduces the improved technologies in all plants, in order of their cost effectiveness. The resulting cost vs. energy savings relationship is usually converted (assuming a discount rate) to an energy price vs. energy savings relationship, a CSC. In contrast, historical CSCs are based on actual behavior of industries or plants. Using longitudinal (e.g. the LIEF analysis) or crossectional data (on energy intensities, energy prices and other variables), we infer the energy-efficiency response to price differences. This goes beyond elasticity determination because the form of the analysis identifies best practice or "ideal" energy intensities. That is, the CSC is an inference as to the best historical performance, as a function of prices.

Our current focus is frontier, or best-practice, analysis. Huntington (1995) discusses the relationship between frontier analysis and traditional engineering analysis at some length. We employ plant level data for our studies using frontier analysis. The best-practice plants are those which have minimum inputs per unit of output for any mix of inputs. One of the great strengths of frontier analysis is that the individual situation of each plant is approximately taken into account. One does not ask how far a plant is from a national-average "minimum-cost plant" or an idealized engineering model of a plant ; one asks how far each plant is from the neighboring frontier as defined by the best observed practice of other similar plants. The distance to that frontier is measured by reducing all plant inputs, keeping the ratios among inputs fixed.

The techniques we employ allow us to measure many aspects of efficiency. The simplest is based on a cross-sectional comparison of plants. One can measure how much of the plants' inputs of labor, energy, etc. might be reduced if each plant were using the observed best practice. Table 1 summarizes one such results for energy use in 6 4-digit SICs. These estimates of 'conservation potential' are based on efficiency improvements in all inputs, not just energy alone. That is, the potential energy savings is the difference between the average plant and the average best-practice plants, not the difference between the average plant the least energy intensity plant. Best practice is defined in terms of several inputs, not only energy.

In more recent analysis we have focused on more narrowly defined sets of plants: a sample of plants that is relatively homogeneous in production process and product, such as steel minimills, cement plants (Boyd et al 1994), or integrated chemical-pulp and paper/paper board mills (Boyd 1995). These steel and paper industry samples are not simply classifications based on 4-digit SICs, but are regroupings of subsets of the 4-digit sectors.

Consider the minimill study (Bock et al 1994,) as an example of what can be learned from analysis of plant-level data. The best practice mills use about 20% less electricity per ton than the average. A tentative conclusion for this industry is that improving its technical efficiency is potentially a big opportunity, but historical trends suggest that it might be difficult to achieve. While the overall electricity intensity of the industry is flat, dissection of it shows strong trends: decline with newer vintage EAFs, decline with learning (as measured by cumulative production), increase from new applications of electricity (e.g. for pollution control), and increase from declining capacity utilization. Based on crossectional analysis of the timing of EAF adoption in the steel industry overall (Boyd & Karlson 1993) we observe the small role of electricity price in determining the technology shift to the EAF. This suggests that decisions about fundamental technology are driven by strategic considerations rather than simple cost considerations like energy price.

TABLE 1 Estimates of Energy Consumption under Best Practice Technology Assumptions (source: Boyd et al, 1992)

SIC Code and Industry	Actual Total Energy Input (10^9 Btu)	Best Practice Total Energy Input (10^9 Btu)	Energy Conservation Potential (Average - Best Practice) % decrease
2621 Paper mills	1,080.2	880.4	18.5
2812 Alkalies and chlorine	147.9	147.6	0.2
2873 Nitrogenous fertilizers	192.9	176.6	8.4
3241 Cement, hydraulic	337.7	269.4	20.2
3312 Blast furnaces and steel mills	1,854.6	1,416.5	23.6
3334 Primary aluminum	245.9	231.1	6.0

When making comparisons of plant efficiency across time we employ other variations of the best practice measurement techniques which allow changes in productivity to be decomposed into two parts (**Fare et al 1989**). The components are the *change in technology*, i.e. the rate at which input intensities of the best-practice plants have been declining (movement of the frontier), and *change in technical efficiency*, i.e. the change in how far the average plant lags behind best-practice plants.

The possible reasons for technical inefficiency, or the lag of a typical plant behind the frontier, are many. As mentioned above, some are likely to be site specific aspects of plant or process design and could not be reduced simply by general improvements in management practice or by policy initiatives. However, when management practice is a key element of plant inefficiency then gains could be made. Study of what happened in the period after the energy-price shocks could shed light on this; and we believe it might show substantial reductions in technical inefficiency. Such an analysis would try to distinguish between investment projects adopted because the higher prices made them more attractive, versus changes in the decision making or managerial practices (i.e. reduction of technical inefficiencies). Examples of these managerial changes included setting of energy-efficiency-improvement goals, changing managerial responsibilities (like assigning energy managers), energy measurement and reporting programs, contests, technology information programs, and increased willingness to try new technologies.

The techniques just described focus on technological change and technical efficiency, but not cost efficiency. Two technologies may be best practice, but only one may be the cost efficient solution. It is possible to introduce prices into the frontier analysis and measure an additional type of *cost efficiency*. In the analysis discussed above this additional step was not taken. One reason, alluded to above, is that cost efficiency analysis *tends* to assume that all plants are in the same situation, that only one type of production technology is cost minimizing, in spite of the variabilities. Another reason is that technical efficiency is a necessary (although not sufficient) condition for cost efficiency. To the extent that substantial technical inefficiency is found to exist, and to the extent that the conservation literature correctly implies that many new technologies are preferred (over a range of recent prices), then the measurement of technical efficiency will yield important insights. To perform analysis of cost efficiency an additional analytic framework need to be developed. The next section discusses technology choice in a cost minimization framework.

ADOPTION OF NEW TECHNOLOGY

Fundamental vs. incremental technology

Technological change has been the major driver of improved products and reduced manufacturing costs -- i.e. productivity improvement. We categorize change in production-process technology as fundamental and incremental (**DOE 1991**). Fundamental new technology is defined as substantially altering the relations among inputs at a plant, such as labor, capital, materials and energy within a year-to-year change. Incremental change is defined as not substantially altering the *ratios* of inputs (or changing the ratios only in established directions), at least in the short term.

Incremental technology can be important. In recent decades incremental change has been increasing because of computers: Computers have created burgeoning opportunities for sensing characteristics of the product stream and the physical conditions of each operation. Detailed automatic control has become feasible. New opportunities continue to open up with the development of new sensors, new computing capabilities including software, and new control mechanisms. The potential for improvement of the product and for cost-reduction by "learning", already found to be large in previous decades, has increased.

Figure 1 shows fixed proportions of inputs for production-process technology A. Here energy inputs are shown collectively on one axis with other variable inputs like labor and materials and capital on the other; in general frontier analysis is many-dimensional. With incremental change, one obtains technology AA, in which all input requirements are lowered in the same proportion. Figure 2 shows two different technologies one of which, B, represents a fundamental change from A. In principle, B is not initially competitive. Through R&D, technology B is improved incrementally (to BB) and it becomes competitive with AA. One can ask many questions of frontier analysis; the answers may even be solid and of great interest. We can ask, for example:

- What has been the structure of shifts to fundamentally new technology?
- Do some plants appear to adopt a fundamentally new technology early (e.g. at B)?
- Is the learning that follows innovation rapid; is it shared among many plants?

Answers to such questions might illuminate how different policies affect the adoption rates for the two kinds of technology. Boyd and Ross (1993) discuss how risk and uncertainty about performance can delay adoption of BB, even when it surpasses AA in its cost efficiency. This framework may be applicable to further understanding why some plants innovate and move toward the frontier, while others do not.

The definitions of fundamental and incremental technical change are not necessarily in accord with common parlance, where fundamentally new technology might refer to the application of new science. However, if fundamental change in popular terms involves investing in major facilities, our definition will usually agree. Typically one tracks fundamental technology by the adoption of readily-named major facilities: EAF steelmaking, continuous digesters for pulping, dry process cement mills, etc. Incremental technology typically involves smaller investments and, in addition, improvements in management. It is important to note that with our definition, incremental change could still be rapid.

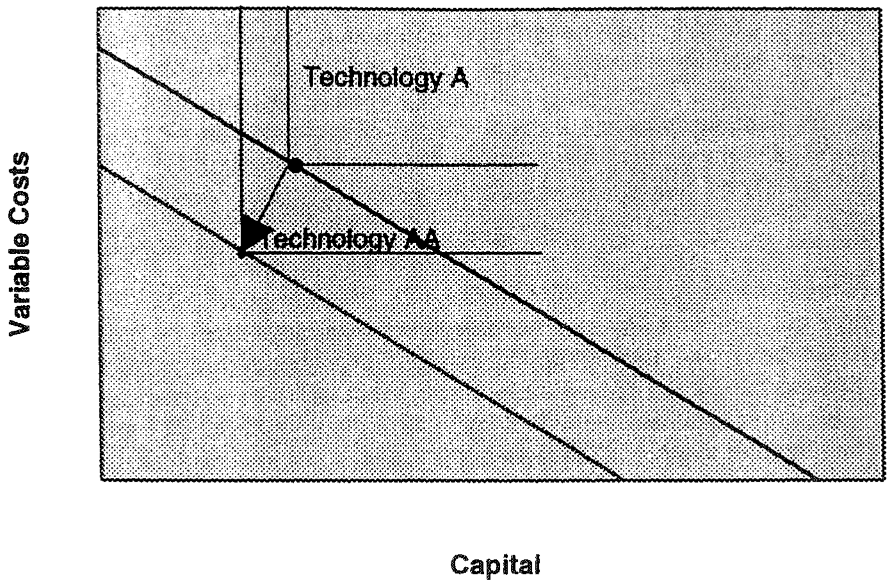

Figure 1 Example of Incremental Technical Change

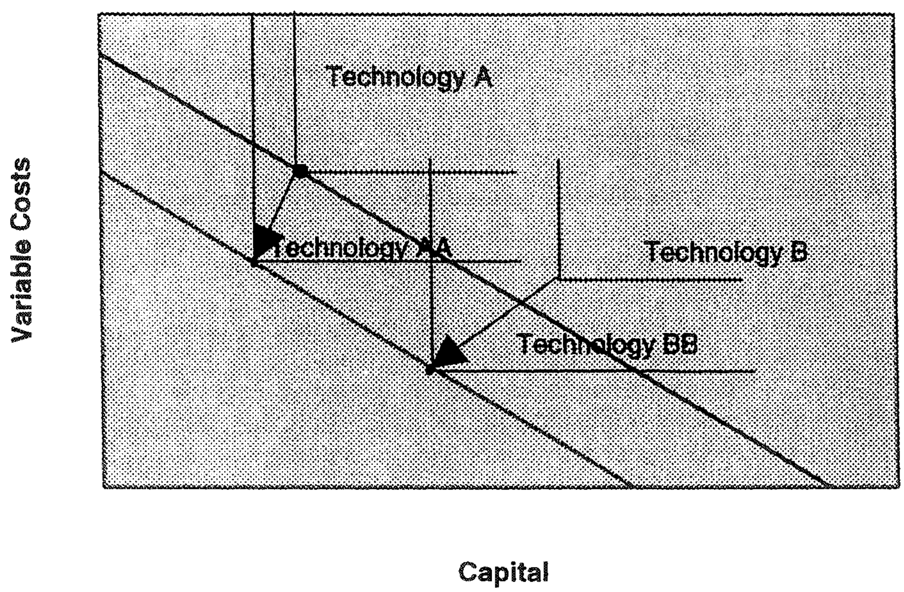

Figure 2 Example of Fundamental Technical Change

It has been shown for many industrial processes that the learning following introduction of fundamentally new technology yields much greater productivity benefits than the innovation itself, i.e. the initial adoption of the technology. One can often say that the major benefit of introducing a fundamental technology is the learning opportunities it creates, opportunities largely exhausted with mature technologies. New fundamental technology combined with learning, combines, in a sense, fundamental and incremental change, although it will usually be identified as fundamental. The question of the timing of adoption for a plant for firm depends on how the learning is appropriated. If learning is appropriated by labor, then wages tend to rise and the firm does not benefit as much (in terms of cost reduction) by the learning. At the other extreme, if the learning is easily transferred outside of the firm to the industry then the firm again obtains little competitive advantage by being an early adopter. In a study of plant level learning at the Center for Economic Studies, Bahk and Gort (1992) found that all three of these effects occur for a wide range of industry sectors. Industry-wide learning and technological change embodied in new equipment was the largest source of productivity gains, but plant specific learning was also observed.

Research & development, demonstration, and diffusion (R&D^3): The pace, the race, and the pack

The frontier production analysis provides a way of measuring two components of productivity change: technological change and the change in technical efficiency. Technological change describes the reduced level of input requirements achieved by best practice. Technical efficiency change describes the improvement that a plant, firm, or industry makes relative to the best practice. The analogy of a race is useful in understanding these descriptors. Technological change is how fast the leader is running, while technical efficiency change is describes whether the pack is catching up or falling behind. This framework and race analogy gives us insights into the dynamics of an industry.

Consider the leading or best practice plants first. The rate of technological change in the best practice is clearly bounded by the underlying opportunities in the industrial process. This relates to the R&D part of the R&D^3. This is the focus of major government and private research programs. We can analyze how much of the progress of the past decade or two (in particular industries) has been associated with incremental change vs. that made in association with fundamental change.

The measurement of technological change does not directly enable one to distinguish between the availability of improved technology and the rate of innovation (or diffusion). It may, however, enable characterization of typical innovators:

- What do the leaders look like?
- Are they best practice?
- Are there a few plants that set the pace, or is the race a game of leap-frog, where worst jump over the pack and become leaders for a brief time?
- Are there times when the best practice is far ahead, with the pack trying to catch up over some extended period?
- How critical is learning over the years that immediately follow innovation?

Of course, the analysis at the Census Bureau can only address these in a statistical sense, due to confidentiality restrictions. The case of a single leader is typical of the Schumpeterian view of the 'innovator'. However, we have not yet learned whether, in the industries we have studied, innovators tend to be best practice. Nefier (1995) has found some evidence of this in the cement industry. We are beginning to create the right combined data sets to address this issue. Let us for the moment assume that firms and plants that try new technologies consistently define best practice. In the context of the risk/adoption model these decision makers involved have low risk aversion. If the industry is competitive, then the rest must try to keep up. The innovative firm/plant then represents the demonstration part of R&D^3.

Finally, consider the pack of followers. Assuming that the innovators are best practice, the followers represent the diffusion part of R&D^3. The structure of the industry may be

- each plant in its place, or
- with much movement from back to front.

The policy issue that underlies the diffusion of new technology is whether or not one can compress the pack, so that all firms move closer to the frontier, and whether this would yield much benefit. Best practice analysis of the energy crisis period should shed light on this compressibility for any particular industry. This compression appears to be the goal of programs, such as technical assistance, and DSM incentives, that try to enhance the diffusion of new technology. Such policies want technology to be *adopted faster* following initial demonstration. Measurement of technological change and efficiency change will enable evaluation of the potential role of RD&D policies to accelerate movement of the frontier versus the potential role of diffusion policies to compress the distribution behind the frontier.

CONCLUSION

Frontier production, or best-practice, analysis based on combining Census plant-level data with other data sets, promises to be increasingly useful for analyzing historical patterns of industrial decision making on production-process technology. This empirical work is in its infancy because major efforts are needed to create powerful combined data sets. The approach should enable, for example, some evaluation of the productivity benefits of:

- pursuing fundamental vs. incremental technologies,
- choosing innovation or waiting for technology to be thoroughly demonstrated, and
- accelerating the creation of new technology and its initial adoption vs. trying to enhance the diffusion of technology.

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