TRADING CAPITAL FOR ENERGY

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PREFACE

The views expressed herein are those of the author and not necessarily those of ACEEE. After starting work at Monsanto in 1959 as a Process Designer, Daniel Steinmeyer progressed through a wide range of responsibilities, retiring in 1997 as a Distinguished Fellow. He can be reached at:

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SUMMARY

Capital is traded against energy in all aspects of life. In other words, we pay more initially to achieve lower operating costs. An example is when we buy appliances with increased efficiency, paying a little more for them initially in order to reduce their operating cost. This trade is even more important whenever engineers design equipment. Engineering practice follows well-defined rules and when these rules are converted to economic terms, three remarkably powerful lessons emerge. First, the economic impact of energy efficiency decisions for new facilities is low (see Figure 1 and its discussion). "The world is flat" summarizes the fact that deviations as great as 50 percent from optimum energy efficiency can have small economic impact.

Second, doubling the price of energy by introducing an energy tax can lead to a 34 percent drop in process energy use (see Figure 2 and its discussion). And third, major long-term reductions can be achieved without destroying industry's competitive position (see Figure 3 and its discussion.) The key is that the money raised by the tax needs to be returned to provide an incentive for a capital replacement program. This return of the money is the “revenue-neutral policy.”

The size of a tax increase and the balancing investment rebate has to be large enough to have an impact on the investment decision process. Yet the *net* economic impact has to be small enough to stay inside the “noise/risk level” of the investment process, in order to not drive the process industries[1] overseas. This appears to be feasible.

[1] The capital-energy trade is particularly important for the process industries (such as chemicals, oil, and paper) that dominate industrial energy use.

The capital-energy trade is augmented by the benefits of new technology (i.e., learning), even though learning appears to be a distinct and separate topic (see Figure 4, Example 4 and their discussions).

CONTEXT

The debate about global warming has led to much discussion about how to reduce energy use. Industrial energy use represents about one-third of the total. Since industrial use is sensitive to price, initial proposals suggested an energy tax as a simple mechanism to drive a reduction in energy use. A relatively large tax, in the range of the current base energy price, would be necessary to achieve the targeted 35 percent reduction in energy use. As initially proposed, the energy tax would only be imposed on the developed world. The major argument for focusing on the developed world is that the developed world dominates energy use and should demonstrate leadership in the drive toward reduced energy usage and greenhouse gas emissions.

An energy of tax of this magnitude has some obvious problems. First, a tax of this size would probably cause relocation of the process industries to regions in the developing world that didn't adopt this tax. Second, new facilities built in the developing world would *not* be affected by the high energy price and would *not* be pushed to trade capital for energy. One of the results of discussing how to avoid these problems is a proposal of a "revenue-neutral energy tax." This report is a result of the merger of the revenue-neutral discussion with long-term analysis by the author regarding the question: "*What happens when capital is traded against energy—quantitatively?*" The answer that came from the merger of these topics was: *"If handled properly, a revenue-neutral tax policy could be a very good idea."* More specifically, a revenue-neutral tax policy with a large energy tax could achieve something in the range of a 35 percent reduction in energy use without destroying the process industries in the developed world. Included in this report is a first pass at how to implement a revenue-neutral policy.

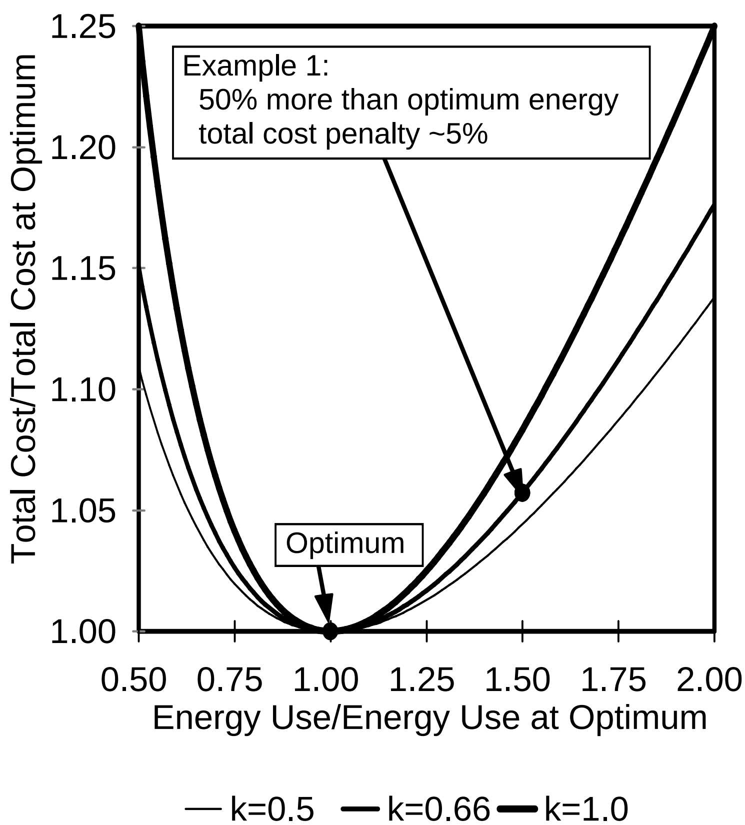
A separate discussion exists in government and industry on the questions of "*how to encourage technological change (learning)*—and—*how to predict its impact.*" Trading capital for energy is fundamentally different from learning. The capital-energy trade occurs with frozen technology and the analysis shown by Figures 1, 2, and 3 ignores learning. However, the topics of the capital-energy trade and learning overlap because any new facilities that are built as a result of a policy that encourages replacement will inherently be more efficient because they are newer. This is illustrated by Example 4. These benefits can be added to the benefits of the trade of capital for energy. The learning benefits extend well beyond energy efficiency and perhaps only approximately 1/10 of the total learning benefit lies in the energy area. This is also illustrated by Example 4.

In the long run, *technological change is a more important topic than the trade of capital for energy* but it is an enormous topic in its own right and it is only lightly treated here.

THE SHAPE OF THE TOTAL COST CURVES

Engineers and economists like to draw curves showing how capital cost can be traded against energy cost. Usually these curves carry no numbers. The engineers and economists usually report a fairly flat minimum point on the curve, like Figure 1 shows—and then move on to another topic.

Figure 1. Impact of Energy Use on Total Cost.



The most tangible numbers we typically see are on the required "energy cost of operation" stickers on new appliances. More efficient appliances (e.g., efficient refrigerators, air conditioners, or furnaces) usually cost more. When the combined purchase and energy costs (i.e., the lifecycle cost) for all the alternate appliances are plotted, there is a least-cost appliance. This is the optimum appliance. From a practical standpoint, this set of options means that the buyer has a fair degree of freedom. If she is short of money today, she will buy the less-efficient unit and absorb the higher lifetime energy costs. If she has ample cash and knows that she'll be keeping the device for many years, she is much more likely to choose the more efficient one. The same type of options exist for the engineers and business managers choosing the efficiency of equipment for new plants.

The Importance of Being Quantitative

Saying that "a cost balance is made" is commonsense and by itself a rather dull story. It only gets interesting when the results are quantified and converted into options that enable other actions.

When engineers design a new plant and business managers pick and choose between options for that plant, the analysis is likely to be much more quantitative but the same issues are at play as in buying an appliance. Since the industrial decision is more quantitative, understanding the shape of the curves in the "region of the optimum" becomes important. The quantitative story is basically told by Figures 1, 2, and 3. The detailed bases for the capital/energy trade shown in these figures are given in the appendices and the annotated references. Key points follow.

- The relations between capital and energy are rooted in engineering design relationships and align tolerably well with other data.

- The curves are *extremely shallow in the region of the optimum* (see Figure 1). For example, if the designer chooses to use 50 percent more than the optimum amount of energy, the economic penalty is only in the range of 4 to 8 percent. If he errs on the side of less than optimum energy, the economic penalty is even less.

THE TRADE OF CAPITAL FOR ENERGY AND THE RULES BEHIND THE TRADE

Balancing Energy Costs Against Capital Costs

Higher energy use permits smaller equipment and lower capital costs. One example is that the use of smaller diameter pipes results in higher pressure drop in the pipes. Higher pressure drop leads to more energy input by the pump or compressor. Other examples are given below. The repeated theme is: "*There is an optimum economic balance between energy costs and capital costs.*"

Industry has always traded energy cost against capital costs in pursuit of lowest cost of production. When industry can reduce the cost for either equipment or energy, it does so. It continually pushes at both to minimize total costs. Industry really doesn't care in the choice between them, it cares about their total.

Fixed Cost Lifetime Ratios of Energy/Capital Costs

It turns out that, for an optimized design, most components of a facility have a fixed ratio between capital and energy cost. Examples are: the trade of heat loss through insulation against insulation thickness and insulation cost; the balance between pressure drop in piping systems and the pipe size and cost; and the balance between unrecovered energy and heat exchanger size and cost.

*In optimized designs, the costs of energy and the capital it is traded against are in a **fixed cost ratio**. If the price of energy doubles, the designer will spend more on making his capital equipment more efficient to lower his energy cost. When he finishes his adjustment, the cost ratio of energy to capital will be where it was before the price increased.*

Intuitively we expect a physical ratio to be maintained, but that isn't the way the balance works. The ratio that is maintained is the ratio of costs. These can most easily be envisioned on a lifetime basis, but the unit of time over which capital and energy are compared can be much shorter. The ratio of energy/capital cost will remain the same if the "time value of money" is properly accounted for.

This ***fixed cost ratio****, which we'll call "****k,****" sets the impact of a change in energy price on energy use. The ratio also sets the penalty for deviating from the economic optimum—"the shape of the curve."*

The background for why fixed cost ratios exist is discussed in the appendix, Parts A and B. Parts C and D show how the impact of the fixed cost ratios echos through into economics.

Each of the little capital against energy trades turns out to have a technical base, which can be reduced to an energy/capital cost ratio for that class of design decision (see the appendix, Part E). The overall energy/capital cost ratio for a process plant is a composite of many minor trades in the design of the plant. Hence it turns out that process plants of a certain type have overall ratios of capital to energy costs that appear to be nearly the same (see the discussion in the appendix, Part F).

THE SHAPE OF THE CURVES IN THE TRADE OF CAPITAL FOR ENERGY

When Energy Is Not at the Optimum Usage, What is the Economic Penalty?

For energy policy, the most important role of the energy/capital cost ratio ***(k)*** is that it defines the shape of the total cost curve. The total cost is the combination of energy cost and the capital it is traded against. It is also conveniently expressed as a ratio and simply referred to as the **total cost ratio.**

In the appendix, Part B, a derivation is given for total cost ratio that shows

$$\textbf{total cost ratio} = \frac{\text{total cost}}{\text{total cost at the optimum energy usage}}$$

$$\equiv \frac{(\boldsymbol{k})\dfrac{(\text{actual energy usage})}{\text{optimum energy usage}} + \dfrac{(\text{optimum energy usage})^{\boldsymbol{k}}}{(\text{actual energy usage})^{\boldsymbol{k}}}}{(1 + \boldsymbol{k})}$$

In Figure 1, total cost ratio is plotted against

energy use ratio = (energy use)/(energy use at optimum)

The total cost ratio curves reach their minimum value of 1 when the energy use ratio is also 1. This is the economic optimum. Note that the curves have an expanded vertical scale and that the net cost impact for deviations from the optimum is small for all the curves when the curves are close to the optimum (the low point). These "gentle slopes" near the optimum say that economics sends "weak signals."

Note also that the curves vary somewhat for different values of ***k***. This means that when energy cost is a higher fraction of capital cost, there is a greater penalty for deviating from optimum energy use.

Figure 2 shows how energy use at the optimum varies with energy price. In Figure 2, energy use and price are both again presented as ratios:

$$\textbf{shifted energy ratio} = \frac{\text{(optimum energy use @ new energy price)}}{\text{(optimum energy use @ old energy price)}}$$

$$\textbf{energy price ratio} = \frac{\text{(new energy price)}}{\text{(old energy price)}}$$

The curves in Figure 2 are calculated by:

$$\textbf{shifted energy ratio} = \{\textbf{energy price ratio}\}^{\{1/(1+\boldsymbol{k})\}}$$

A derivation of this is given in the appendix, Part C.

Figure 3. Impact of Energy Price on Total Cost.

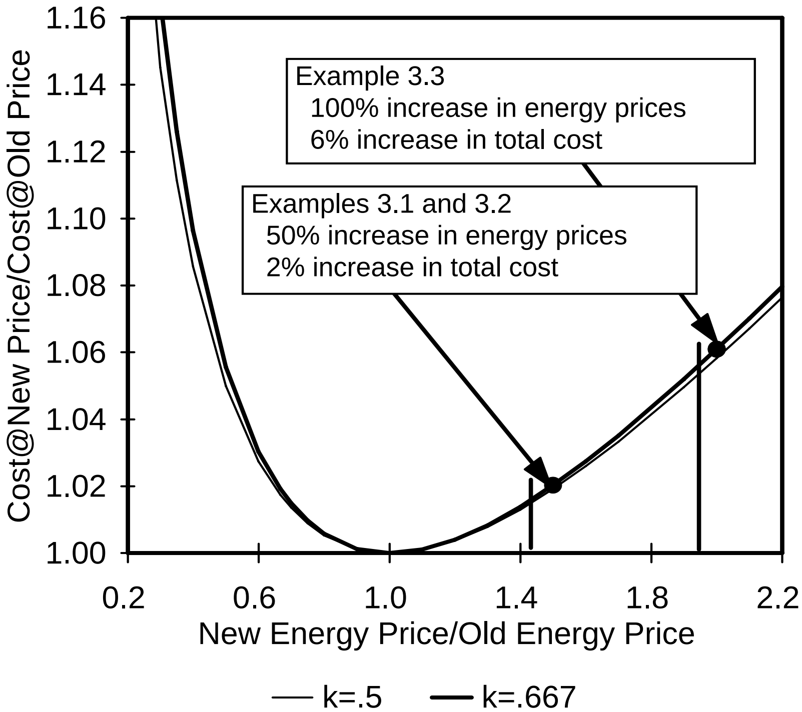
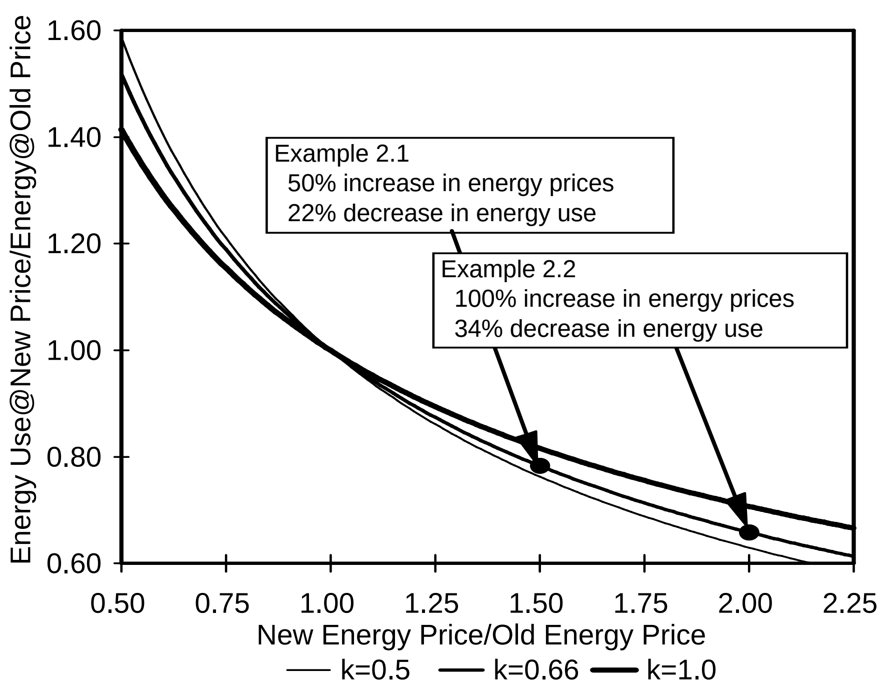


Figure 3 com-bines the results from Figure 1 and Figure 2 and shows how the total cost ratio will change as the energy price ratio changes. A value of 1 for total cost ratio in Figure 3 corresponds to the optimum design of the unit for the actual energy price. A point on the curves for energy price ratio of 1.5 corresponds to an existing plant where the price has risen 50 percent above the price the plant was designed for.

The reason for showing the curves for different ***k*** values is to indicate that the conclusions are modified only slightly as the value of ***k*** changes.

Figure 2. Impact of Energy Price on Total Cost.



What Do the Flat Curves Say about Off-Optimum Operation for the Firm?

Figure 1 shows that *there is little economic penalty for operating with either too much or too little energy as long as the design is within 50 percent of the optimum energy use.*

Example 1: existing plant that is using 50 percent more energy than optimum.

In Figure 1, a use of energy that exceeds optimum by 50 percent results in a penalty for total cost ratio of about 5 percent for the curve with a ***k*** of 2/3. If these costs represent 30 percent of total cost, the net result is a penalty on total production of about 1.5 percent. This would motivate concern but not immediate retrofit action.

Figure 2 shows that *energy price has a great deal of leverage on optimum energy use in a new plant.*

Example 2.1: impact of a 50 percent increase in energy price for a new plant.

Assuming ***k*** of 2/3, Figure 2 shows that a new plant would be designed for 22 percent less energy use.

Example 2.2: impact of a 100 percent increase in energy price for a new plant.

Assuming ***k*** of 2/3, Figure 5 shows the new plant would be designed for 34 percent less energy use.

Figure 3 shows that *there is surprisingly little economic penalty for ignoring an energy price increase.*

Example 3.1: existing plant when energy prices rise 50 percent above the level it was designed for.

Assuming ***k*** of 2/3, Figure 3 shows that the economic penalty for the existing plant using excess energy is only 2 percent compared to a new plant optimized against the correct price. The reason is that the capital not spent largely offsets the excess energy used.

Example 3.2: new plant designed as if the energy price were 50 percent above the actual**.**

Assuming ***k*** of 2/3, Figure 3 shows that the economic penalty for the new plant's excess use of capital is only 2 percent. This could be viewed as the result of a "revenue-neutral energy tax policy" with a 50 percent tax on energy.

Example 3.3: new plant designed as if the energy price were twice as high as actual.

Assuming ***k*** of 2/3, Figure 3 shows that the economic penalty for the new plant's excess use of capital is only 6 percent. This could be viewed as the result of a "revenue-neutral energy tax policy" with a 100 percent tax on energy.

Example 3.3 could be viewed as society seeing the actual cost of energy as 100 percent higher than what the market charges. A reason for this would be environmental impacts. If society votes a 100 percent tax on energy based on environmental impacts, the net use of energy for a new plant would drop 34 percent for a ***k*** of 2/3 because of this tax. The drop occurs as a result of increased capital spent by the firm to offset the higher energy price.

The operator would be out the cost of his capital and energy taxes. But suppose society said that it really didn't care about keeping the taxes and gave them back to the operator as a credit for capital spent. The net is the 6 percent economic penalty of Example 3.3.

For a real production unit, the costs of raw materials, labor, and other capital would dilute the impact further as shown by Example 5.3 on page 23.

Reasons for the Small Economic Impact of Changes near the Optimum ("Flatness")

At first glance the modest penalties in Figures 1 and 3 are puzzling. The explanation for this modest penalty is that if a bit too much insulation (or heat exchanger surface) is used, the added investment earns an economic return, just not quite as high as the return at the optimum. For less than optimal insulation (or heat exchange surface), a similar economic buffering occurs. Because of this "near optimum" return, a fairly large change in energy use can be made with a small economic penalty. This means that a plant that is designed for 80 percent of optimum energy use or 120 percent of optimum energy will achieve about the same economic return on its capital. The difference is likely to be much less than the "noise" in the capital decision-making process.

What the Shape of the Curves Means for Energy Retrofits

The bad news is that the retrofit potential is limited. As noted by Example 1, a use of energy that exceeds optimum by 50 percent gives a relatively modest penalty for energy costs plus tradeable capital costs.

Furthermore, the operator of an existing plant can't fully adjust to the new economic optimum even if he wants to. He does not have the same options open to him that the designer of a new plant does. For example, he can't afford to throw away his 6 inch diameter pipe and increase to 8 inch to match the new economic optimum pressure drop. Another example is adding more insulation to an existing pipe. The designer of a new plant simply looks at the incremental costs of going from 2 inches of insulation to 4 inches of insulation. The plant maintenance engineer looking at a retrofit has to add the costs of going back to change things—scaffolding, adding a new weather barrier, adding new hangers, and the basic costs of re-engineering and organizing the effort. The net is that he faces a prohibitive cost. He will retrofit where he can but this tends to be limited to things added in series, such as additional heat exchangers. In the analogy of an individual buying an appliance, once the appliance is built, there are limited things that can be done to improve the efficiency.

The final impact of a price increase would await unit replacement at the end of its useful economic life. The existing facilities would probably continue to operate for several years. The reduction in energy use due to the price increase predicted by Figure 2 would come, but would be delayed.

What Does the Shape of the Curves Mean for Energy Use in New Designs?

The shape of the curve means that a fairly large amount of capital can be traded for a fairly large amount of energy in the design of new facilities, with little economic impact. This happens via the normal design and capital decision-making processes.

The flat curve shows that the designer has a great deal of freedom in terms of how much energy he chooses to use. For example, he could achieve a one-third drop in heat losses from a fired-heater by increasing the efficiency of the heat recovery system from 85 percent to 90 percent. The differences caused by added heat exchange equipment will not have a great impact on the long-term economics of the plant operation; however, it will have a significant impact on the capital cost of the fired heater. Given the normal project emphasis on controlling capital and coming in 'within budget,' the result is a tendency to make the choices on the side of less capital and more energy. This is consistent with the observation that many new facilities are not designed to achieve all the economically achievable energy recovery. In terms of Figure 1, this means that facilities will tend to be designed for operation to the right of the point where the curves go through 1. But it doesn't have to be that way. Given an alternate set of corporate policies, the designer could move to the left of the point where the curves go through 1—and reduce energy use, with little impact on either the economics of the company or the overall economy.

In other words, new facilities can be designed for higher energy efficiency with little economic penalty. The problem is how to get this to happen within the existing capital decision-making process. A carefully targeted energy tax plus tax rebate scheme could motivate this change.

What Does the Shape of the Curves Say about Differences Between Firms/Countries?

What really matters in the trade of capital for energy is the ratio of their prices. A country that subsidizes energy costs will run a high ratio of capital price to energy price. This encourages new units designed for low energy efficiency. A subsidized energy price is the explanation for the relatively inefficient plants of Eastern Europe. Similarly a company or a country that expects very high return on its capital also runs a high ratio of capital price to energy price and also encourages relatively inefficient plants.

As shown by Figure 2, major changes in relative price will drive major changes in energy use. The reported variation of energy usages (as high as 30 percent) that exist for different firms and different countries operating similar processes can be seen as logical within this context.

What Does the Flat Curves Say about the Revenue-Neutral Tax Policy?

A revenue-neutral policy taxes one thing but makes the tax revenue available for return to the taxpayer to subsidize another thing. In this case, a tax on energy could be returned to subsidize the expenditure of capital used to build more energy-efficient plants.

The revenue-neutral policy is a way to induce the designer to move toward energy efficiency by taxing energy while giving the company the tax money back as a capital subsidy or rebate. This policy requires a carefully focused energy tax credit. It has to be done with precision, meaning that the rebate must be used for the intended purpose by the intended users. One doesn't want a situation where steel companies end up using their capital rebates to build golf courses or buy oil companies. A capital subsidy could take any form as long as the money is channeled back into the replacement facilities. The money paid by a paper mill or ethylene plant would be used to build a replacement paper mill or ethylene plant. While the changed set of prices and capital costs would drive the replacement unit to higher efficiency, the rebate could be a broad investment credit and not limited to energy saving equipment.

Figures 2 and 3 suggest that a shift to 34 percent less energy use by industry can be produced by a doubling in energy price, and can be achieved with a tolerable economic penalty. *A key assumption is that enough time is allowed to permit it to happen as part of the capital replacement process*. To the degree possible, the existing infrastructure of existing capital facilities such as roads, buildings, and tankage would be retained.

THE CAPITAL DECISION-MAKING PROCESS

Information and Noise in the Capital Decision-Making Process

A capital investment decision is a bet on the future made with uncertain information. It relies on assumptions about what a unit will cost in capital, and what its raw materials and energy will cost. More importantly, it is a bet on markets and economic/political stability. Since capital dominates costs, uncertainty about economic/political stability has been very important. Some believe it explains the pattern of exports and imports, with capital investment historically being built in the developed world. Oil, a major feedstock, can be very easily shipped to ports anywhere.

Factors such as risk in markets and economic/political stability cannot outweigh a factor of two increase in energy costs caused by an energy tax, but they can outweigh a small penalty (approximately 2 percent) in the dollar totals for energy and the capital it is traded against. Thus *if industry can be induced to move backward along the curve (toward lower energy use) through a revenue-neutral tax shift, the 2 percent economic penalty is lost in the noise of uncertainty that surrounds the capital investment process.*

A nation can reduce its energy use without causing its industry to relocate or operate at a significant disadvantage, if it keeps within the noise of the uncertainty in the capital decision-making process. This is the underlying principle for the revenue-neutral tax policy.

The relevance of the "shape of the curve" is: *If we can stay on the shallow part of the curve by providing an incentive for the capital-energy trade via a revenue-neutral tax shift, most firms would look past the energy tax and simply choose to build their plants based on market size and economic/political stability. We can make a major cut in industrial energy use in new plants and do it via the capital investment decision-making process.*

Capital Replacement—When? And Where?

Most industrial processes are more heavily influenced by capital than energy. For example, as discussed in the appendix, Part F, in the chemical industry the ratio of energy costs to the capital it is traded against is approximately 2/3. As a result, facilities will continue to operate in a region long after that region can effectively compete for new capital investments because of high energy costs. Some will continue to operate even if a large energy tax is imposed. See Example 4.2.

Closing a plant or scrapping equipment has drawbacks. To the extent this can be avoided, society saves its capital. An example of a long and useful life are the acrylonitrile plants in the chemical industry that operate competitively for 35 years. In the electricity generating industry, steam turbines continue to operate for as long as 50 years.

The infrastructure in an industrial plant (the roads, tankage, buildings, and such) remain effective long after the individual processes they originally served have passed into obsolescence. They have historically been reused for other replacement processes. This is necessary to efficiently use the nation's capital. It is also necessary to enable the revenue-neutral policy to work effectively.

Location of New Plants

However, at some point in time a decision will be made that older facilities will be shut down. Before this happens, support (such as technical staff and maintenance) for these facilities will be withdrawn. The shutdown of facilities will follow, as continued wear and tear and process improvement (technological innovation) make them more obsolete.

The key question then becomes: "Where will the replacement facilities be built?" One could argue that energy costs are insufficiently large to dictate capital relocation to another region. However, the relocation of the sectors of U.S. industry that use high amounts of energy to regions of low energy costs, like the Gulf Coast, argues otherwise.

Capital Replacement—Why?

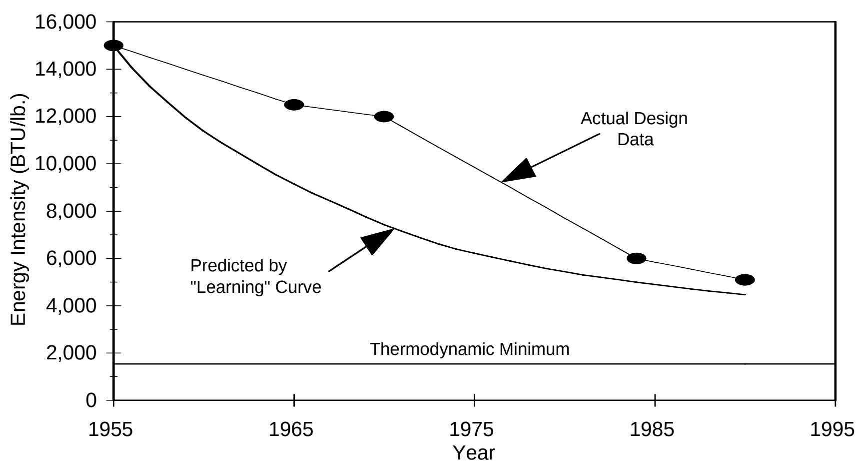
Old processes eventually are replaced. This happens whenever the inefficiencies of operating the old facility become large enough to offset the capital charge of starting over. In many industries, this happens every 20 to 40 years even in the absence of major marketplace changes, due to "wear and tear" that induces lower economic efficiency, as well as concern with issues such as safety. An even stronger reason to replace processes is technological change. Technological change includes the ongoing *learning* process as well as major "breakthroughs."

Learning

The learning process can be summarized in the approximation: *"With every doubling of cumulative production, costs drop 20 percent."*

An example of learning is the design energy efficiency of ethylene plants, as portrayed in Figure 4. Note that the actual design numbers approximate those predicted by the learning curve relationship. Ethylene is a relatively new (post- 1940) material so the cumulative production doubles more quickly and the yearly efficiency gain occurs more swiftly. The good news from an energy standpoint is that a 30-year-old plant can no longer compete without major retrofits and is likely to be replaced by a new plant.

Figure 4. Design Energy Efficiency of New Ethylene Plants and Efficiency Predicted by a Learning Curve Relationship.



Energy as a Fraction of Total Learning

For the chemical industry as a whole, energy represents about 10 percent of value added. One consequence often heard is that R&D that focuses only on reducing energy use will rarely achieve enough leverage to dictate a change in facilities.

Another consequence is that the "new" facility carries learning benefits in many areas in addition to energy. For example, safety and product quality are generally better, maintenance costs are lower, and environmental discharges are generally much less when an old plant is replaced by a new plant. When 90 percent of total economic costs are not energy, it is reasonable to expect that most of the economic benefits from learning would also fall outside the energy area. A large part of learning benefits comes in the area of capital. Part of this is in newer equipment and construction concepts, and part is learning how to build to a larger scale. In principle, there is a “world-scale” that limits size and is tied to the fact that there is a limit on the size of individual components that can be shop-fabricated and shipped to construction sites. However the reality is that “world-scale” keeps getting bigger as designers learn ways to bypass these limits.

Breakthroughs

Technological breakthroughs can be envisioned as bigger steps on the learning curve, or starts of new curves. They might involve a change in raw materials or catalyst or a different processing concept. One measure is that their impact is big enough to cause shutdown of the facilities using the older process.

"Wear and Tear" and Physical Exhaustion as Contributors to Capital Replacement

Normal deterioration of an industrial plant reduces energy efficiency and overall economic efficiency. Examples are deterioration in insulation, corrosion of heat exchanger tubing leading to plugged tubes, and degradation of efficiency of motors and pumps. This, along with the benefits of learning, put the old plant at an economic disadvantage compared to a new facility. In the discussion below, these benefits are lumped under the “learning” heading.

“Wear and tear” explains why the maintenance costs go up more rapidly with age than do other costs, as shown in Example 4.

"One-Time Harvest" of Learning Benefits from the Revenue-Neutral Tax Shift

When a facility is replaced there is a unique opportunity to readjust economic efficiency of all types, including energy. Insertion of a program of capital rebates drives one move on the learning curve. For newly built plants, the revenue-neutral tax shift will not dictate an immediate shutdown/replacement, but for a plant nearing the normal end of its lifetime, the operator will be motivated to replace the unit. The new unit that is built will carry the benefits of learning in the intervening years since startup, in addition to being optimized against the different energy price.

Example 4: replacement of plants of different vintages.

Suppose a company has three older plants and is evaluating their replacement with new units that incorporate the latest learning. Suppose the new plant has the following annualized costs:

	relative	-----------------------------------$ million-----------------------						
	energy use	$\$_{energy}$	$\$_{maintenance}$	$\$_{new\ capital}$	$\$_{labor}$	$\$_{raw\ materials}$	$\$_{other}$	$\$_{total}$
new plant	1	10	10	35	5	15	5	80

The $\$_{maintenance}$ cost includes factory indirect charges for taxes, insurance etc. It is part of the charge associated with capital equipment. The $\$_{new\ capital}$ cost is the charge for depreciation and return on investment. The sum of these two charges is often used in payback calculations. The difference between this combination of charges and "return on investment" is part of the background of why industry talks of payback times of 2 to 3 years while economists expect something in the 5 to 10 year range.

The three older plants are all fully depreciated, and have no charge for new capital, but carry increasing cost penalties in other areas:

	relative	-----------------------------------$ million------------------------						
	energy use	$\$_{energy}$	$\$_{maintenance}$	$\$_{new\ capital}$	$\$_{labor}$	$\$_{raw\ materials}$	$\$_{other}$	$\$_{total}$
old plant	1.2	12	18	0	6	18	6	58
older plant	1.3	13	26	0	6.5	19.5	6.5	71.5
very old plant	1.4	14	34	0	7	21	7	83

The three plants are intended to represent the continuum of existing manufacturing units.

Example 4.1: even in the absence of energy taxes, the learning curve benefits and avoidance of wear and tear degradation justify replacement of the "very old" plant.

The $38M of higher operating cost for the "very old" plant more than offsets the new capital charge of $35M. However, the new capital can't be justified for the "old" or "older" plants. Despite the lower energy and other costs, avoidance of the higher capital cost of a new plant makes an overwhelming case to continue operation of the "old and "older" plants.

Example 4.2: the learning curve benefits plus an energy tax still are *not* convincing enough to shutdown the "old" and "older" plants.

Suppose a 100 percent energy tax is imposed on all plants, old and new. This causes the company to reoptimize the design of the new plant to use less energy and more capital. This is the same case as shown by Example 5.2 but the charges are broken down slightly differently.

	relative energy use	$\$_{energy}$	$\$_{tax}$	$\$_{maintenance}$	$\$_{new\ capital}$	$\$_{labor}$	$\$_{raw\ materials}$	$\$_{other}$	$\$_{total}$
		----------------------------------$ million---------------------------							
reoptimized new plant with 100 percent energy tax	0.66	6.6	6.6	11.11	38.89	5	15	5	88.2

The energy tax causes the "old" and "older" plant costs to increase sharply, but the reoptimized new plant still shows higher costs:

	relative energy use	$\$_{energy}$	$\$_{tax}$	$\$_{maintenance}$	$\$_{new\ capital}$	$\$_{labor}$	$\$_{raw\ materials}$	$\$_{other}$	$\$_{total}$
		----------------------------------$ million---------------------------							
old plant with 100 percent energy tax	1.2	12	12	18	0	6	18	6	72
older plant with 100 percent energy tax	1.3	13	13	26	0	6.5	19.5	6.5	84.5

Example 4.3: the learning curve benefits plus an energy tax with full rebate as an investment credit (revenue-neutral tax)—*are* convincing enough for replacement of the "older" plant.

Suppose the energy tax comes with a full rebate as an investment tax credit (the revenue-neutral policy) and the new plant is reoptimized for the high energy cost. This is the same case as shown by Example 5.3.

	relative energy use	$\$_{energy}$	$\$_{tax}$	$\$_{maintenance}$	$\$_{new\ capital}$	$\$_{labor}$	$\$_{raw\ materials}$	$\$_{other}$	$\$_{total}$
		----------------------------------$ million----------------------							
reoptimized new plant with 100 percent energy tax and rebate of energy tax as an investment credit	0.66	6.6	0	11.11	38.89	5	15	5	81.6

With this set of economics the company would replace both the "very old" and "older" plants. The "old" plant would continue to operate. Four points to note from Example 4:

- When the “very old” and “older” plants are replaced, the energy use will essentially be cut in half.

- The energy savings are almost equally split between reoptimization (the expenditure of capital traded against energy) and learning.

- The benefits of learning extend well beyond energy.

- The oldest, least efficient, least economic plant is shut down first.

If the benefits of operating a new plant rather than an old one are so great, why is a tax rebate needed? By returning the energy tax to the company when new investment is made, the change will happen more quickly and the new plant will be kept from being built overseas.

Learning Is a Very Important Topic and Merits its Own Separate Discussion

Learning is enhanced by production experience, R&D, technological diffusion, a competitive economic structure, and a questioning cultural structure. The sources of learning, and its measurement and prediction are all important topics and little discussed. Learning is a separate topic, to be treated in a separate report. The main relevance to trading capital for energy is that it makes the capital-energy trade a more powerful option for reducing industrial energy use.

INDUSTRIAL REVENUE-NEUTRAL ENERGY TAX POLICY

Possibilities for Implementing the Revenue-Neutral Tax

One way to achieve the carefully focused, efficient tax necessary is to return the tax to the firms that pay it and require that it be used for investment in facilities in the same production area as the tax was paid. The focus must be on new facilities because capital can be traded for energy more efficiently in new facilities.

If a rebate for the energy taxes is fully and precisely returned as a capital credit, the firm will see the new plant costs shown in Figure 3. The firm will optimize the new plant for the capital-energy trade based on the higher price of energy reflected in the energy tax, but will not be penalized for the tax itself. The net economic penalty as seen by the firm is small and within its economic noise level. This is illustrated by Example 4.3 and Example 5.3.

The only real requirement is that the investment credit needs to be used for production facilities in the same industry (e.g., ethylene manufacture) that paid the tax. There are a number of variants on how this might be achieved. The energy-tax-turned-investment-credit could be pooled for an industry and returned to individual firms as qualifying investments are made. Or it could be set aside for individual companies and made available for sale to the highest bidder within the industrial group. Or it could be returned to individual companies and set aside into escrow accounts for use when the individual companies execute replacement projects. The escrow option is the one singled out for discussion below, although in some ways, allowing a sale or bidding process would have advantages.

The Escrow Account —For Individual Companies

Industry fears that government would divert the energy tax revenue for "other good uses." Companies also worry that competitors might aggressively manage their books to extract more money than they put in. A way to avoid the concern on all parts is to set up escrow accounts for individual companies. A firm that paid its energy taxes for 10 years would have a large share of the capital available for a new facility.

Functionally, this is similar to the credit card rebates managed by the automobile companies. Balances would build up for each individual firm, to be used for a specific purpose. Here the balance could only be used for investment in new facilities for the same commodity for which the tax had been paid. The analogy for the credit card is that the balance can only be used to purchase a new car from the company that manages the credit card.

A Simple Self-Documenting System

Administering this scheme would not have to be difficult. The firm withdrawing from this account would present documentation of payment toward construction of new facilities. It would also attest that the withdrawal was in the same process area (SIC code) for which tax had been paid. Self-testing of this type for qualification is basically the approach used for the energy tax credits of the early 1980s.

The United States had an active program of energy tax credits in place in the early 1980s. It rewarded efficiency improvements but focused most strongly on renewable energy. The reward level for efficiency was relatively low and while the reward sent the right signals and acted as a banner for efficiency, the actual motivation was minimal. In contrast, the incentive level for renewables was quite high. Windfarms, solar thermal, and photovoltaic investments were driven forward to a large extent by tax rebates. While these technologies, particularly windfarms, are making a growing energy contribution, many of the early installations were based on uncertain technology and have subsequently been shut down. To the extent that this happened we wasted the nation’s capital.

What have we learned from this? First, any rebate has to be relatively large in order to have a large impact. Second, tax rebates for risky, undemonstrated technology should recognize the needs for limiting loss.

The Case for Low Risk Energy Efficiency

In contrast to renewable energy, energy efficiency technology generally is at the minimal risk level. Typically, energy efficiency is just "more of the same." Here "more" speaks to specifics like insulation thickness and heat exchanger surface. Even the economic rate of return is known with unusually high certainty.

Tax credits distort investment. *Key to a successful tax credit is that it provides incentives for something that is very nearly economically sound in its own right.* Energy efficiency is perhaps uniquely qualified because so many decisions are made at the margin of an economic return, and they are made by firms in their normal investment process.

Externality Effects

The case for enhanced energy efficiency is based on "externality effects," which simply means that there are costs borne outside the market process that the individual firm does not see directly. An example of an externality effect would be toxic material discharged to the air. Release of CO_2 and other byproducts of energy use also carry externality effects. If the real economic cost, due to environmental or security issues, is substantially higher than what the market charges, society has good reason to display this real cost and provide incentives for industry and other users to adjust their economic decisions.

Companies do a poor job of incorporating externality effects in their decision-making processes. It might appear otherwise because many companies practice "enlightened self- interest" and behave as benignly as their economics permit. Enlightened self-interest exists because companies have strong reasons to preempt governmental action by good behavior and to also achieve a climate that enables them to function with lessened bureaucratic control. But this is not a well- calibrated process and some companies feel much less reason to practice enlightened self-interest than others.

Experience with a wide range of companies suggests that action to reduce energy use is unlikely to win priority above what economics dictates. Attempts to sell a lower marginal return for energy projects due to externality effects get a bit of lip service but gathers intense, sometimes emotional opposition from managers who have spent their careers trying to demonstrate their allegiance to “bottom line” values.

In reality, the opposite tilt tends to happen. Energy cost-reduction is rarely strategic and it usually shuffles down on the priority list, well below issues of production, quality, and safety. A bit of marginal energy that is not saved has never gotten a project manager fired.

Tax Credits and High Risk—The Case for Renewables

An alternate rationale for tax incentives that is sometimes offered is that they compensate for the risk of uncertain technology and that tax incentives let the government make the high risk moves that accompany commercialization of new technology. This was one driver behind the windfarm and solar thermal subsidies. The argument for this type of government incentive is open to debate. Industry deals with risk in all its activities. Companies that deal with it well survive and prosper. Those that do not, wither or move to other business quickly.

Government has no such “survive and prosper” motivation and is easily bullied and misled into nonproductive ventures. If the government attempts to choose winning technologies, it can waste the nation's capital if it chooses poorly (e.g., the synthetic fuels program of the late 1970s and early 1980s). The revenue-neutral tax proposal would leave investment and technology decisions up to individual companies.

Problems with the Revenue-Neutral Industrial Energy Tax Policy

It Is Not Understood

The tax rebate involves a concept that is new to both industry and government with regard to taxes. It also involves a quantification of the energy-capital trade that isn’t obvious. An underlying problem is that industry has to be convinced that a major change is possible, as well as desirable, in the way it deals with energy. This report is part of the dialog that needs to occur.

What Energy Is Not Taxed?—Feedstock and Electrochemical

This proposal would tax energy used for fuel and power but not feedstocks. In practice, feedstock and process use are often very difficult to distinguish and a large tax on process energy use, but not on feedstocks, would motivate a great deal of activity by regulators and accountants. Conversely, not taxing feedstocks has a logical base at least in the chemical industry because feedstocks are largely preserved in the framework of the molecules that move in as hydrocarbons and move out as chemical products. The yield on entering molecules is typically in the range of 70 to 90 percent for the chemical industry.

Electrochemical energy is generally not tradeable against capital, and some mechanism needs to be setup to protect the industries that rely on it (e.g., aluminum smelting).

Non-Process Industries—Do They Follow Different Rules?

The process industries (chemicals, oil/coal, primary metals, paper, food and glass/clay/stone) account for 88 percent of industrial energy use. They share enough characteristics that a case can be made that their trade of energy for capital will fall into the same general band as the chemical industry and can be adequately represented by the curves of Figures 1, 2, and 3.

This is not true of the fabricating industries such as electronic and transportation equipment. Conversely, energy as a fraction of value added in these non-process industries is in the range of 0.3 percent to 1 percent. As a result, investment decisions are unlikely to be influenced by any energy tax or energy tax rebate.

If the Money Is Given Back, Will the Companies Perceive It as No Tax at All?

This is a key issue. A firm will be motivated to build replacement facilities but it could simply choose to build them at an energy efficiency level similar to what they have historically used, on the basis that the real energy price after the rebate hasn't changed very much. This possibility would be considered by a firm that envisions an unending, long-term capital program that will always fully utilize the rebate stream, as shown by Example 5.4. However, the firm is unlikely to believe it really has this option. There are only so many facilities of a given type that will be built and there is a limited amount of product that can be sold. Competition between firms will keep this from being seen as a realistic option for the firm.

How Should We Define the Envelope for Neutrality in Time and Place?

Often the discussion of rebating energy taxes gravitates towards rewarding workers (i.e., income or Social Security tax reductions). This will not work from the perspective of encouraging less energy use and maximum capital stock replacement. Labor (as we know it) is rarely traded for energy. When it is, it is not recognizable as labor in the sense normally considered, but as engineering time invested in the capital process.

Ideally, capital is returned to individual firms for specific facilities and is only returned when these facilities are built. Ideally, the rebate is returned to the same site that bore the energy tax, thereby minimizing worker dislocation.

More generally, if an energy tax is returned to the taxpayer as a subsidy for any action other than capital investment, we reduce movement along the total cost curve in the capital/energy trade.

Timelag

Because of its link with capital investment, response to this energy tax policy will not be immediately apparent. There will be a timelag of at least 10 years before the full impact will be felt. It may not even be possible to spend the capital needed to implement this program in 15 years, due to limits of the market infrastructure for supplying new equipment and construction management.

Unintended Consequences Can Occur

Capital can be diverted to unproductive uses, such as facilities that are built but not operated or are underutilized. We have many skeletons from past energy programs. Capital has been wasted on projects as diverse as solar thermal generating facilities and plants for converting coal to synthetic fuels. Bright, energetic people can be lured into careers as tax specialists and regulators. We could add another area for government regulation. Capital costs could be driven up by large demand. *But none of these are preordained to happen.*

An objective of the policy should be to keep these from happening, and to make as little distortion to the economic system as possible. Energy tax policy too should be subject to a learning curve. The relatively low success rate of our previous policy initiatives suggests caution, humility, careful planning, and *testing* before implementing major programs such as the one suggested here. The relatively dramatic shifts in our previous policy initiatives suggest we should be skeptical of major new ones. For example, the programs of the late 1970s and early 1980s to manufacture synthetic fuels from coal were an economic disaster.

Other Things that Might Cause this Policy Not to Work

There are six possibilities why this policy might not work. First, industry could find the capital rebate process too cumbersome. Second, political pressures could cause the rebate to flow for different objectives like job creation, or to flow to nonmanufacturing sectors. Third, tax specialists could somehow distort the intent and operation. Fourth, it could be too small to impact the capital decision-making process. Fifth, industry might not believe either the increased tax or its rebate are permanent. And sixth, the timelag before we saw results could be too long to sustain support. *But none of these are preordained to happen.*

How Will We Know That this Policy Worked, or If It Did Not?

If it works, we will see a major increase in capital spending on manufacturing within 5 years and a major decrease in energy use by manufacturing within 10 years. If it does not work, we will see neither of the above.

And if it doesn't work—we repeal the legislation. We return to things as they were, with a few newer plants, a few less older plants, and some unused escrow accounts. This is not a happy ending but it is not nearly as serious as the consequences of some of the alternates that have been proposed to reduce energy use.

If the Revenue-Neutral Policy Works

Example 5: given a large energy tax, how does the firm respond in the design of its new facilities? Assuming:

- we double energy price by imposing a tax
- we start with an optimum design for ***k*** of 2/3 and energy costs of $10 million per year (i.e., the optimum tradeable capital we start with would be $15 million per year)
- the capital that is not tradeable against energy is $30 million and the capital that is not tradeable against energy is retained when the initial plant is replaced

- feedstock, labor and other are \$25 million

Example 5.1: the base new plant.

---------- base ----------		-------------------------$ million-------------------------						
energy price	E_{opt}	$\$_{energy}$	$\$_{tax}$	$\$_{tradeable\ capital}$	$\$_{other\ capital}$	$\$_{other}$	$\$_{total}$
1	1	10		15	30	25	80

Example 5.2: if a 100 percent energy tax is imposed, and the new plant design is *reoptimized.*

-------- ratioed to base-		-------------------$ million------------------------------					
energy price	E_{opt}	$\$_{energy}$	$\$_{tax}$	$\$_{tradeable\ capital}$	$\$_{other\ capital}$	$\$_{other}$	$\$_{total}$
2	**0.66***	6.6	6.6	20**	30	25	88.2***

* A doubling of process energy price (due to the tax) results in a design with 34 percent less energy use.

** The rise in energy price and the subsequent reoptimization against capital results in a reduction in energy use but causes a major rise in the tradeable capital.

*** The total costs increase, as compared to a plant in a part of the world without the tax: \$80=>\$88.2 (a 10 percent increase).

Example 5.3: if the tax is rebated for the new *reoptimized* plant.

-----ratioed to base–		-----------------------------$ million----------------------------					
energy price	E_{opt}	$\$_{energy}$	$\$_{tax}$	$\$_{tradeable\ capital}$	$\$_{other\ capital}$	$\$_{other}$	$\Sigma\$$
2	**0.66***	6.6		20**	30	25	**81.6**

If the tax is rebated, the increase in costs is only \$80=>\$81.6 (a 2 percent increase).

Example 5.4: if the tax is rebated for a new *unoptimized* plant.

-----ratioed to base–		-----------------------------$ million----------------------------					
energy price	E_{opt}	$\$_{energy}$	$\$_{tax}$	$\$_{tradeable\ capital}$	$\$_{other\ capital}$	$\$_{other}$	$\Sigma\$$
??? 1	?	10		15	30	25	80

These are the economics that would exist if a firm executes an unending stream of expansion projects and could always use the tax rebate stream. *However, as* *discussed above, competitive pressures keep this from being a realistic option.* A more likely outcome is shown below:

(Probable outcome)

-----ratioed to base–		------------------------------$ million----------------------------					
energy price	E_{opt}	$\$_{energy}$	$\$_{tax}$	$\$_{tradeable\ capital}$	$\$_{other\ capital}$	$\$_{other}$	Σ$
1	?	10	10	15	30	25	90

AN EXTRAPOLATION

This analysis suggests that industrial process energy use could be cut by approximately 1/3 for an approximately 2 percent added cost to industry. This requires retention of the "other support capital" in the replacement of existing facilities. This, in turn, means that for overall economic efficiency, capital stock replacement cannot be rushed.

TO RECAP

The most important points are:

- The energy-capital trade follows quantitative rules. These are rooted in engineering design fundamentals.
- The quantitative rules suggest that industry can trade a great deal of energy and capital with minor long-term economic penalties to its competitive position.
- One tool to achieve this is a revenue-neutral energy tax along with a tax rebate for investment in new manufacturing facilities.

ACKNOWLEDGMENTS

Many of the ideas that are presented here trace back to discussions with Marc Ross, Howard Geller, Neal Elliott, Skip Laitner, and Gale Boyd.

APPENDIX

Definition of Variables:

C = constant in expression relating capital cost to energy use

E = energy used per unit of time, e.g., Btu/year

E_o = energy used per unit of time at the optimum

$E_{o\ new}$ = energy used per unit of time at the optimum, at new energy price

$E_{o\ old}$ = energy used per unit of time at the optimum, at old energy price

k = energy/capital cost ratio at the optimum energy use
= $(\$_{total}/\$_{capital})$ at the optimum energy use
= **fixed cost ratio**

$P_{capital}$ = capital price constant, e.g., for heat exchange, \$ per ft^2 per year

P_{energy} = energy price, e.g., \$/Btu

P = $P_{energy} / P_{capital}$

$\$_{capital}$ = cost of capital that is traded against energy, e.g., \$/year
= $[C/E^{\boldsymbol{k}}][P_{capital}]$

where
$C/E^{\boldsymbol{k}}$ is a capital use relationship, e.g., for heat exchange it defines ft_2
(In most areas of equipment design, capital equipment size and cost go down as energy use goes up. The relationship
$1/E^{\boldsymbol{k}}$
defines this dependence of capital on energy use. The background is briefly outlined in Part E. See References 1, 2, and 6 for more detail.)

$\$_{energy}$ = cost of energy, e.g., \$/year
= $E[P_{energy}]$

$\$_{total}$ = $\$_{capital} + \$_{energy}$

shifted energy ratio ≡ $\{E_{o\ old}/E_{o\ new}\} = \{P_{energy\ old}/P_{energy\ new}\}^{1/(\mathbf{k}+1)}$

energy price ratio ≡ $\{P_{energy\ old}/P_{energy\ new}\}$

total cost ratio ≡ ratio of combined cost of energy and capital it is traded against, to the value that would exist at the optimum energy use
≡ $(\$_{capital} + \$_{energy})/(\$_{capital} + \$_{energy})_{at\ optimum\ energy\ use}$

Part A: Derivation of the Identity

$\boldsymbol{k}$ Equal to $[\$_{energy}/\$_{capital}]_{optimum}$

Approach:

When $\$_{total}$, which is the sum of $\$_{capital}$ plus $\$_{energy,}$ is plotted against energy use as in Figure 1, there is a low point on the curve. The low point on the curve is the minimum cost point, or the *optimum*. When we find the low point on the curve we discover that it occurs when $\$_{total}/\$_{capital}$ equals $\boldsymbol{k}$.

By definition,

$$\$_{capital} + \$_{energy} \equiv [C/E^{\boldsymbol{k}}][P_{capital}] + E[P_{energy}] \quad \textbf{\{I\}}$$

taking the derivative of **{I}** with respect to E and setting to zero gives the low point on the curve, or the economic *optimum*, and since at this point E equals E_o

$$0 = -\boldsymbol{k}[C/E_o^{\ \boldsymbol{k}+1}][P_{capital}] + P_{energy}$$

rearranging

$$\boldsymbol{k} = E_o[P_{energy}]/[C/E_o^{\ \boldsymbol{k}}][P_{capital}]$$

$$= [\$_{energy}/\$_{capital}]_{optimum} \quad \textbf{\{II\}}$$

Part B: Derivation of Total Cost Relationship (Shown by Figure 1)

Approach:

Similar to [A], an expression for $\$_{total}/\$_{total\ at\ optimum\ energy\ use}$ is developed. When the curve for this ratio is plotted against energy use and we find the low point on the curve, we can use the resulting value for optimum energy use to simplify the expression.

Again by definition,

$$\$_{capital} + \$_{energy} \equiv [C/E^{\boldsymbol{k}}][P_{capital}] + E[P_{energy}] \quad \textbf{\{I\}}$$

also by definition, the combined cost that would exist at the optimum energy use is

$$(\$_{capital} + \$_{energy})_{at\ optimum\ energy\ use} \equiv (1+\boldsymbol{k})[C/E_o\boldsymbol{k}][P_{energy}] \quad \textbf{\{Ia\}}$$

Therefore the ratio of **{I}/{Ia}**, the **total cost ratio** is

$$\textbf{total cost ratio} = \frac{\{[C/E^{\boldsymbol{k}}][P_{capital}] + E[P_{energy}]\}}{\{(1+\boldsymbol{k})[C/E_o^{\ \boldsymbol{k}}][P_{capital}]\}} \quad \textbf{\{III\}}$$

rearranging

$$\textbf{total cost ratio} = \frac{\{E[E_o]^{\boldsymbol{k}}(P_{energy}/[CP_{capital}]) + [E_o/E]^{\boldsymbol{k}}\}}{(1+\boldsymbol{k})} \quad \textbf{\{IIIa\}}$$

Taking the derivative of **{IIIa}** with respect to E and setting to zero gives the low point on the curve, or the economic optimum. When this is solved for E_o we find

$$E_o = \{\{CP_{capital}/P_{energy}\}\boldsymbol{k}\}^{1/(\mathbf{k}+1)} \qquad \textbf{\{IV\}}$$

or

$$P_{energy}/[CP_{capital}] = \boldsymbol{k}/(E_o)^{(\mathbf{k}+1)} \qquad \textbf{\{IVa\}}$$

substituting $P_{energy}/[CP_{capital}]$ from **{IVa}** into **{IIIa}** gives the relationship

$$\textbf{total cost ratio} = \frac{(\boldsymbol{k})(E/E_o) + (E_o/E)^{\boldsymbol{k}}}{(1+\boldsymbol{k})} \qquad \textbf{\{V\}}$$

Part C: Derivation of Impact of Energy Price on Energy Use at the Optimum (shown by Figure 2)

Approach:

When **{IV}** is used to calculate optimum energy use for two different prices, and the ratio of the two energy uses is calculated, the term $CP_{capital}\boldsymbol{k}^{1/(\mathbf{k}+1)}$ cancels out.
Designating the new energy price $P_{energy\ new}$ and the old price as $P_{energy\ old}$, and the corresponding optimum energy uses as E_o and $E_{o\ old,}$ we obtain from **{IV}**

$$E_{o\ new} / E_{o\ old} = \{P_{energy\ old}/P_{energy\ new}\}^{1/(\mathbf{k}+1)}$$

or

$$\textbf{shifted energy ratio} = \textbf{\{energy price ratio\}}^{1/(\mathbf{k}+1)} \qquad \textbf{\{VI\}}$$

Part D: A Bit More on the Impact of Energy Price on Energy Use

the ratio of energy price to capital price

Since we are dealing with the trade of capital for energy it is often more useful to deal with energy price as its ratio to capital price:

$$\boldsymbol{P} = P_{energy}/P_{capital}$$

The optimum energy use, $E_{o,}$ varies with a change in the ratios of these prices:

$$E_{o\ new}/E_{o\ old} = \{\boldsymbol{P}_{old}/\boldsymbol{P}_{new}\}^{\{1/(1+\boldsymbol{k})\}}$$

Example 6.1: impact of energy price relative to capital price for a facility.

If $\boldsymbol{k}$ is 0.66 and energy price doubles relative to capital price due to a tax on energy, we would expect to see the new optimized system designed to use 34 percent less energy:

energy use as fraction of prior $= [1/2]^{1/1.66} = 0.5^{0.6} = 0.66$

Example 6.2: impact of energy price relative to capital for a heat recovery system.

If $\boldsymbol{k}$ is 1.5 and energy price doubles relative to heat exchange surface price due to a tax on energy, we would expect to see the new optimized system designed to use 24 percent less energy:

energy use as fraction of prior $= [1/2]^{1/2.5} = 0.5^{0.4} = 0.76$

If the old system recovered 85 percent of the possible energy, the new one would recover 100 - 15(0.76), or 89 percent of the possible energy.

Part E: Framework behind the Curves

why do we use so much energy
The explanation comes in a sequence of concepts:

Driving forces are needed to move energy and materials through our processes, and driving forces cost loss of work potential.

Higher driving forces permit lower capital.

There is an optimum economic balance between energy and capital costs.

engineering design relationships and k
In most areas of equipment design there is a balance made between capital and process energy costs that arises because capital equipment size and cost go down as energy use goes up. See References 1, 2, and 6 for more detail. The story in brief :

$\$_{capital}$ is proportional to $1/(E)^{\boldsymbol{k}}$

The key factor is the exponent on energy use, $\boldsymbol{k}$.

Many physical relationships involve a flow that varies with resistance and driving force. The resistance typically varies inversely with size (cost) and the driving force varies with energy input raised to some exponent.

flow is proportional to $(\text{size})^{\text{exponent 1}}(\text{driving force})^{\text{exponent 2}}$

Example 7.1: cost ratio, k, for piping.

The flow of fluid varies approximately with

$(\text{pipe diameter})^{2.6}(\text{pressure drop})^{0.5}$

Capital cost also can be described empirically in terms of size and an exponent. For example, piping cost varies approximately with $(\text{pipe diameter})^{0.9}$

When these exponents are combined, they form the basis for the $\boldsymbol{k}_{piping}$.
$\boldsymbol{k}_{piping} = (0.9)(0.5)/2.6 = 0.17$

Example 7.2: cost ratio for pressure drop in turbulent heat exchange.

The flow of heat is proportional to

(heat transfer area)^1(heat transfer coefficient)^1

The heat transfer coefficient in turbulent flow varies approximately with

[(power dissipated)/volume]$^{0.25}$

which, as discussed in Reference 6, translates to

[(pressure drop)/(heat transfer area)$^{0.25}$

and nets a relationship that heat transfer area in turbulent flow varies approximately with

(pressure drop)$^{0.333}$

Capital cost varies approximately with

(heat transfer area)^1

When these exponents are combined, they form the basis for the $\boldsymbol{k}_{\text{pressure drop heat exchange}}$

$\boldsymbol{k}_{\text{pressure drop heat exchange}}$ = 0.333/1 = 0.333

A ***k*** of 0.333 means that in an optimized design, if the annualized energy cost for operating a piece of equipment is $333, the associated annualized capital cost would be $1000. The annualized capital cost includes maintenance, depreciation, return on investment, and taxes. Typically, this annualized capital cost is somewhere in the range of 25 to 50 percent of the total installed cost.

***k* for various trades** *(see Reference 7 for additional discussion)*
k takes the following values for specific physical and engineering design relationships in the capital/energy trade:

	k energy cost / capital cost
- insulation	1
- heat exchanger thermal energy	~ 1.5
- heat exchanger friction losses	~ 0.3
- distillation column volume	~ 0.1
- piping friction losses	~ 0.2
- electrical cable size	1

These individual ***k***'s exist throughout the process industries. The prime reason the individual processes differ is the relative energy use for thermal energy and pumping (piping) energy. All process plants have heat exchangers and piping, although the split between them varies. When there is a higher relative use of thermal energy use, as for example in paper mills and refineries, there is a greater use of heat exchangers and ***k*** will approach 1. In chemical plants, piping is typically a higher fraction and it tilts the overall balance toward dominance by capital, or a ***k*** closer to 0.2.

We tend to think of industrial energy use in terms of thermal energy (and smokestacks) but electricity is typically equal or bigger. Most electricity is used in motors, mainly to raise pressure to balance pressure drop in piping and heat exchangers.

Part F: Agreement of Engineering Design Relations With:

energy/capital for 10 chemicals
These contribute approximately 80 percent of the chemical industry energy use. Data is from Reference 7, based on information in Reference 8.

ethylene	0.2
ammonia	0.2
propylene	0.14
benzene	0.05
sodium hydroxide	0.6
methyl t-butyl ether	0.13
chlorine	0.3
p-xylene	0.2
phosphoric acid	0.15
carbon black	0.5
average	~ 0.2

At first glance, these energy/capital ratios look far too low compared to those of the individual components of the trade, but on closer inspection these values are reasonably consistent with what would be expected from the energy components.

This is because about 40 percent of capital is fixed in items such as roads, labs, and engineering design. This part is not subject to the energy trade. An additional 30 percent of capital is volume related but not energy related. Examples would be storage tankage and reaction vessels.

Therefore

process energy/*tradeable* capital ~ (0.2)/(1 - 0.4 - 0.3) = 0.66

overall chemical industry data
Reference 7 also gives overall chemical industry costs, which show a similar dominance of capital over process energy. Yearly investment of new capital is ~$30 billion and yearly process energy costs is ~$10 billion.

economic price elasticity estimates
Again, price elasticity equals -1/(1+***k***):

k	0.2	0.5	0.67	**0.82**	1	1.5
elasticity	-0.833	-0.67	-0.60	**-0.55**	-0.5	-0.4

These are long-term values, or equilibrium adjustments enabled by capital changes. The time constant on this response would be in the range of 5 to 10 years. The elasticities that characterize a quick response to a rise in prices would be much lower.

The price elasticity data, based on historical analysis of changes in energy use in response to changes in energy price, has a great deal of scatter but the best data that approximate a longer term impact (Reference 11, discussing electricity) suggest an elasticity of -0.55 or a ***k*** somewhere in the range of 0.8. This too is in general agreement with the technical component ***k*** values derived from engineering and physical relationships.

Part G: What Do the Bits and Pieces of Data on *k* Add Up To

They suggest that the energy/capital cost ratio at the optimum "***k***" is somewhere in the range of 0.5 to 1. *The importance is that, as shown by Figures 1, 2 and 3, the conclusions one reaches are essentially the same when **k** falls in this range.*

ANNOTATED REFERENCES

The author's work of the trade of capital for energy goes back 20 years and rather than repeat it, a series of papers are referenced and their significance is discussed.

(1) *Energy Price Impacts Designs*, **Hydrocarbon Processing**, 205-210 (November 1976)

This introduced the quantitative discussion of the trade of capital and energy and the economics of the simple exponential relationships. It also treats two cases of economic heat recovery in heat exchangers.

The major points were:

- The optimum use of energy had fallen dramatically due to the energy price increase in the years preceding this 1976 article.

- Failure to recognize the shift often did not have a major impact on profitability, due to the flatness of the cost curve in the region of the optimum.

Three other points were highlighted. These continue to be prime corollaries:

- The flat cost curves mean that the designer has some freedom in choosing project tone. He can achieve major savings in energy to satisfy a corporate objective or he can live within a tight capital budget.

- There are many more productive ways to save energy than simply sliding along the capital-energy curve.

- Different rules apply to existing plants than to new ones.

(2) *Take your Pick: Capital or Energy*, **Chemtech**, 188-192 (March 1982)

This sharpened the focus on ***k***, the ratio of energy to capital costs at the economic optimum. It also recognized that energy uses in industry fall into 4 categories: work inherent in the chemical reactions; work inherent in purification; simple inefficiencies as in loss through insulation; and driving forces needed to cause fluid flow, heat transfer, reaction and separation. The last two categories are in engineering design and subject to the trade between capital and energy.

(3) *Process Energy Retrofits*, **Chemical Engineering Progress**, 47-50 (June 1984)

This focused on the barriers of uncertainty, activation energy, and ignorance and how they distort the capital/energy balance in an existing plant.

(4) *Energy for Industry* (with Marc Ross), **Scientific American**, 26 & 88-98 (1990)

This was a general review of how energy efficiency comes about in industry. It highlighted the distinction between trading capital for energy and fundamental improvements in processing that arise because of technological change. It further clarified the distinction between the slow incremental progress of learning curves and the start of new curves or breakthroughs. It presented a graph showing the 7 year timelag between capital expended to reduce energy use and the energy price signal that preceded it.

(5) *Energy Use in Manufacturing*, in **The Energy-Environmental Connection**, Island Press, Washington DC (1992)

This expanded on and clarified the basis for learning curves and breakthroughs. It suggested that the extensive experience with energy, economic, and environmental policies in the past two decades pointed to actions. One is that we should be skeptical of radical shifts. It counseled persistence in pursuit of policies like support for education and basic research.

(6) *Understand* Δ*P and* Δ*T in Turbulent Flow Heat Exchangers*, **Chemical Engineering Progress**, 49-55 (June 1996)

This showed that the ***k*** of 1/3 that is characteristic of pressure drop in heat exchangers falls out of a general correlation that explains all turbulent heat transfer. It also showed that the bill for unrecovered heat in a process is typically in the range of 100 to 200 percent times the bill for incremental surface, or ***k*** ~1.5.

(7) *The Impact of High Energy Price Scenarios on Energy-Intensive Sectors,* in **The Chemical Industry in the USA, the Role of Energy and the Impact of Energy Prices**, U.S. Department of Energy, (July 1997)

This was a broad review of the impact of an energy tax on the chemical industry. The distinction between the impact of this energy tax and the revenue-neutral policy is that the money from the energy tax was taken from industry and then just disappeared.

Key points:

- *An energy tax that is only applied to the developed world will cause the high energy portions of the chemical industry to relocate to countries not subject to the tax.*

- *An energy tax that is only applied to the developed world will give a minor net global saving in energy.*

Data on individual processes and the overall chemical industry for the relative costs for energy and capital were melded into the discussion. More background was given on ***k*** values derived from engineering design relations.

Other points:

- Capital equipment improvements that appear to only lower the cost of capital equipment, like finned heat exchangers or plastic pipe, end up netting energy efficiency gains because of the lock of cost ratios. In fact, many of the significant contributors to increased energy efficiency have actually been ways to make equipment at lower cost.

- National information and national market/political stability have a major role in deciding where plants are built and will offset minor economic arguments.

Selected Other References

(8) E. S. Lipinsky and J. D. Ingham, ***Brief Characterizations of the Top 50 US Commodity Chemicals***, Battelle, Columbus, Ohio (1994)

This provided the basis for the energy/capital ratios for the major chemical processes.

(9) Chemical Manufacturers Assoc., ***US Chemical Industry Statistical Handbook 1996***, Washington, DC (1996)

This provided the basis for many of the cost comparisons for the chemical industry.

(10) Energy Information Administration, U.S. Department of Energy, ***Manufacturing Consumption of Energy 1991***, Washington DC (1994)

This provided data for many of the details of energy use, such as the high fraction of electrical use for driving motors, as well as the fraction of energy used by the various industries.

(**11)** M.H. Ross, P. Thimmapuram, R. E. Fisher, and W Maciorowski, *Long-Term Industrial Energy Forecasting Model*, Argonne National Laboratory, Argonne, Illinois (1993)

This provided estimates of the price elasticity for electrical energy.

(12) K. Nelson, *Are There Any Energy Savings Left?*, **Chemical Processing**, 77 (January 1989)

This gives a breakdown of the source of savings achieved by a major plant at Dow in its energy retrofit projects. Only about half the actual savings in the more recent “energy projects” were in energy, with yield, maintenance, and capacity all important.

(**13)** W.H. Joyce, *Reinvestment Value Determination of Price—A Technique to Estimate Price for an Industrial Commodity with Positive Volume Growth Rate*, Ph.D. Dissertation, New York University, (1983)

This showed how learning contributed broadly to cost reduction in new polyethylene plants and how energy costs fell along with other production costs.