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SUPPLY CURVES OF CONSERVED ENERGY

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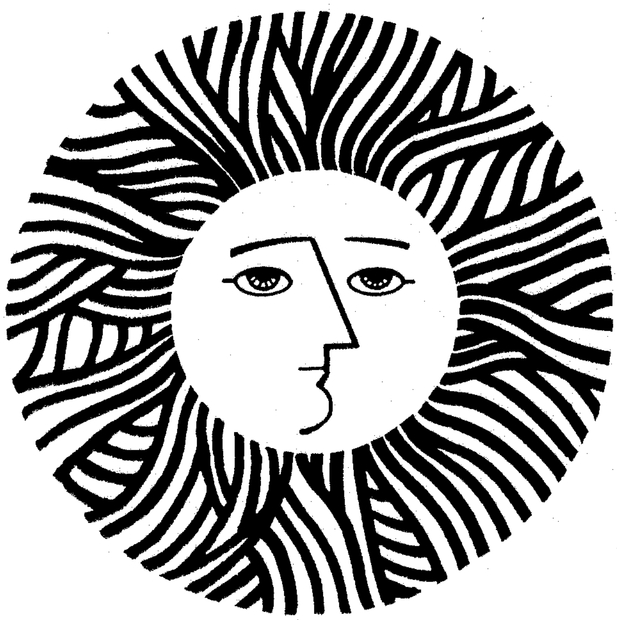
(Ph.D. thesis)

May 1982





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# SUPPLY CURVES OF CONSERVED ENERGY

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Supply Curves of Conserved Energy



by

Alan Kevin Meier

## SUMMARY

Supply curves of conserved energy provide an accounting framework that expresses the potential for energy conservation. The economic worthiness of a conservation measure is expressed in terms of the cost of conserved energy, and a measure is considered economical when the cost of conserved energy is less than the price of the energy it replaces. A supply curve of conserved energy is independent of energy prices; however, the economical reserves of conserved energy will depend on energy prices. Double-counting of energy savings and error propagation are common problems when estimating conservation potentials, but supply curves minimize these difficulties and make their consequences predictable. The sensitivity of the cost of conserved energy is examined, as are variations in the optimal investment strategy in response to changes in inputs. Guidelines are presented for predicting the consequences of such changes. The conservation supply curve concept can be applied to peak power, water, pollution, and other markets where consumers demand a service rather than a particular good.

## ACKNOWLEDGEMENT

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# 1. ORIGINS OF SUPPLY CURVES OF CONSERVED ENERGY

## 1.1 Earlier and Other Energy-Demand Models

Dozens of energy-demand models have been developed in the last two decades.[1] They can be divided into four categories: extrapolations, econometric analyses, end-use analyses, and potentials studies. Forecasters still use all four types, but the classifications have become blurred with time as hybrids (and mutants) have appeared.[2]

Utility companies needed to know future energy demand to plan new supply facilities, especially electric power plants, and became the first institutions to rely on forecasts. These early forecasts -- sometimes called "trend analyses" -- were crude, often straight-line projections of historical trends plotted on semi-log graph paper (to account for exponential growth). Yet these projections were fairly accurate until energy prices began rising and major energy-intensive appliances saturated their markets.

Such projections did not attempt to explain <u>why</u> energy use increased. It did not concern the utility whether the cause was a increased economic activity, more energy-consuming equipment, or higher levels of energy-related services (i.e., higher thermostat settings, more hours of air conditioning, etc.). Energy demand was treated as a monolithic object which, with the exception of certain large industrial consumers, could not easily be altered.

Recognition that energy was a good having a demand that could be influenced by other economic factors brought econometric analysis to bear.[3-5] Population changes, prices of other goods, and unemployment could be factored into the demand for energy. Econometric analysis required more research into how demand changed as a result of many other economic variables.[6,7] Energy demand became much less a "black box" than it had been with extrapolation. Consumers now had modelable alternatives to energy use: econometric models allowed consumers to switch fuels ("cross-fuel elasticity"), conserve ("substitution effect"), and adjust energy use with income ("the income elasticity of energy"). Of course, developing the model became more complicated. Time series and cross-sectional data needed to be collected and analyzed before coefficients could be estimated.

Another improvement of the econometric analyses over extrapolations was the ability to create scenarios. Now one could study the change in demand under different assumptions, such as increased energy prices or level of economic activity. This proved especially useful as economic conditions changed. One problem (which did not reveal itself until the early 1970s) was that the analysis covered a period of remarkable energy price stability.[8] The results did not necessarily apply to more turbulent times.

## 1.2 The End-Use Perspective

Before 1970 there existed a peculiar asymmetry in our knowledge of energy production and consumption. While we knew quite accurately the sources of our energy, we were virtually ignorant of its fate. Statistics for the amount of mined coal and pumped oil were carefully collected, but no comparable data existed for the amounts of energy consumed for space heating or by refrigerators. This ignorance carried over to energy reserves: estimates were frequently made (and updated) regarding the reserves of coal, oil, and uranium, but the parallel concept of potentially conservable energy did not exist.[9]

This information imbalance was reflected in the government's energy policies during the energy crises of the 1970s. The chief responses were a series of specific measures to increase energy supplies; vague, nonspecific sacrifices were expected on the demand side. Automobiles were the exception. Performance was easily measurable and gasoline taxes provided good aggregate data. In addition, European cars offered an easy source of comparison. These factors permitted a rational discussion of efficiency improvements, eventually resulting in forward-looking performance standards.

In 1974, the Princeton Summer Study Group assembled the first comprehensive breakdown of energy consumption by end uses and provided a framework for examining the physics of energy conservation.[10] This breakdown showed, for example, that roughly 18% of the nation's energy was consumed for providing space heat, 2% for refrigeration, and 8% for direct mechanical drive.[11]

The group also examined energy conservation from a thermodynamic perspective. While the first-law efficiencies of existing energy-consuming processes were high, the second-law efficiencies were very low. Thus the potential for saving energy was much greater than first thought. A new perspective on energy conservation developed: the question was not how much energy a process would use, but how little energy it could use through technical improvements.

Good end-use breakdowns for most sectors were not available until 1974, even though limited attempts by the Ford Policy Project [12] and by Dole [13] appeared at least one year earlier. These studies examined energy demand for each major end use, that is, space heating, refrigeration, auto transport, lighting, etc. The estimates for each end use were refined until they equaled actual energy supplied. The end-use forecasting technique (or end-use model) examines each major end use and projects its consumption. Separate forecasts of energy use for each end end use were developed. End uses were combined to forecast aggregate energy demand.

Many new features can be explicitly incorporated within the end-use models. The models can describe attributes of a stock of energy-using equipment. Each end use has a stock and an associated average per-unit energy consumption. (Those in the energy-analysis trade typically call these "unit energy consumptions" or "UECs".) The product of the average per-unit energy consumption and the number of units in the stock equals the energy consumed in that end use, that is,

energy consumption in one end use = number of units in stock x average energy consumption per unit .

In addition, stocks can grow or "turn over" (i.e., more efficient appliances replace older appliances as they are retired) during the forecasted period.

End-use models treat changes in energy demand within end uses with varying levels of sophistication. Some models simply include the impact of a slowly growing stock (i.e., more houses to heat), while others include the effects of conservation, stock turnover, fuel switching, and higher energy prices. The Oak Ridge model is perhaps the best known and most complex.[14] Beyond a certain point, however, the increasing detail is offset by uncertainty in the additional coefficients. The Oak Ridge model, for example, requires at least 100 elasticity coefficients for the residential sector. The coefficients must be estimated econometrically, relying on historical data spanning conditions substantially different from those in existence during the forecast period. Furthermore, treating the end uses in terms of their average per-unit energy consumptions ignores obvious diversity within the stock. Special end uses, or responses appropriate to a particular sub-stock, become distorted in the averaging process. For example, the electric space-heating end use typically includes both resistance-heated and heat-pump-heated homes.

The CONAES analysis went one step further and, in the process, avoided some of the drawbacks of the ORNL modeling efforts.[15] It assumed that consumers invested in all cost-effective measures and estimated the resulting energy use in 2010.

From the beginning, end-use forecasts disagreed with the previous models.[16,17] End-use forecasts generally predicted lower energy consumptions than econometric models or trend analyses, but it was difficult to compare the "assumptions" in the models because the perspectives were so dramatically different. For the residential sector, David Goldstein invented the concept of a "phantom appliance" to explain the higher electricity consumption forecasted by trend analyses and enonometric models. This phantom appliance needed to be electricity-intensive and incorporated rapidly into many homes.[18] The inability of utility forecasters (relying on econometric analyses or extrapolations) to explain the precise source of forecasted demand left them squirming in many rate-case hearings.

The need for disaggregated end-use data has also prompted more surveys of appliance saturations, levels of insulation, type of fuel used, and energy consumption in the residential sector.[19] Perhaps the major lesson from these surveys is that the determinants of residential energy consumption are extraordinarily diverse. A consumer showing a higher-than-average energy use is not necessarily living in an uninsulated home with a high thermostat setting.

Another form of demand forecasting is now appearing. It models a single household's behavior over time with respect to energy-related decisions.[20] Many households are modeled until a sufficient distribution of actions is generated with a Monte Carlo simulation. These distributions are aggregated to reflect total consumption.

## 1.3 Potentials Studies and Supply Curves of Conserved Energy

With a better understanding of how consumers use energy, and how much they actually consume, we may estimate the technical potential for conserving. This approach is strongly influenced by recognizing that the second-law efficiencies of most processes are still very low, and that substantial technical improvements are still possible. Potentials studies have imposed one major constraint in their estimates; namely, current levels of energy-related services are maintained. Conservation measures are limited to technical improvements in efficiency. Without this constraint, the technical potential for conservation equals the energy that we now use -- a conclusion of little value.

A study of conservation potentials is not like other forecasts because it is an estimate of what could occur under carefully specified assumptions.[21-24] It provides certain insights not available from other analytical tools. A potentials study quantifies the gap between current energy use and what is technically feasible. A potentials analysis identifies particular end uses for which large amounts of energy could be saved and the measures necessary to save them. If we also estimate the costs of achieving that potential -- the cost of conserving -- we can determine the level that yields the maximum consumer benefits. In other words, the study of conservation potentials addresses the question: is our energy use at the economically optimum level?

A supply curve of conserved energy is one means of expressing such a potential. (See Figure 1-1.) It is based on the assumption that conserving energy requires investments. These investments can be amortized over the period of energy savings to yield a "cost of conserved energy." A supply curve is constructed from a series of conservation measures and looks like a series of gradually rising steps. Each step on the curve represents one measure; its width indicates the energy saved (or, "supplied through conservation") and its height the cost of conserved energy. Measures are cost-effective if their cost of conserved energy is lower than the price of the energy the measure saves.

There are three advantages of the supply-curve approach discussed here. First, it provides a consistent accounting framework for the treatment of conservation measures. This permits a more generalized treatment of the conservation potential, as well as providing guides for predicting the impact of changes in assumptions.

Second, supply curves have proven an excellent tool for establishing energy policy. The consequences of energy-conservation policies are described with respect to both their costs and energy savings. In addition, conservation can be compared readily to costs of obtaining new energy supplies (because both are expressed as the cost of obtaining a unit of energy).

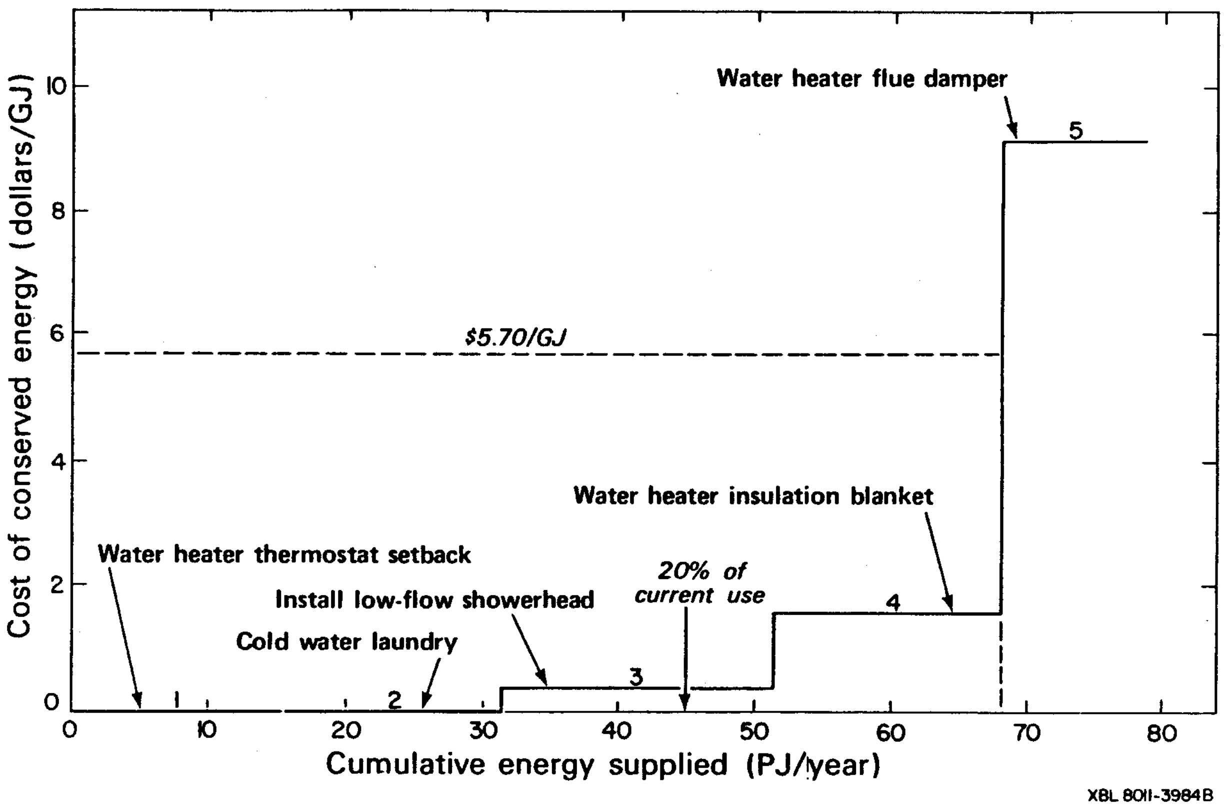


Figure 1-1. A supply curve of conserved natural gas for residential water heating. Each step corresponds to a conservation measure. Here, the curve begins with two free measures, lowering the water temperature in the tank and use of warm water (instead of hot) for clothes washing. Subsequent measures require investment. Conservation measures are cost-effective if their costs of conserved energy are less than the price of the energy they save. Since consumers pay about $5.70/GJ for natural gas, every measure except installation of a flue damper is cost-effective. Total gas used for residential water heating in California in 1978 was 216 PJ. Adapted from Meier et al., "Supply Curves of Conserved Energy for California's Residential Sector."

Third, supply curves of conserved energy offer a framework for incorporating potentials into the traditional supply-demand analysis. In effect, we have shifted a portion of energy demand to the supply side of the equation.

Recently, a series of regulatory commission requirements have created a new application for conservation supply curves.[25,26] Some Public Utility Commissions now require utilities to prove that all cost-effective conservation measures have been implemented before permitting construction of new power plants.[27] Supply curves of conserved energy are proving to be a good framework for making these comparisons. The regulation translates simply into implementing those measures that save electricity at a cost less than that of new electricity.

Why should conserved energy be treated as a supply? The energy market has many imperfections: energy prices do not fully reflect their costs, nor are all consumers able to respond to the existing prices. Treating conserved energy like another supply recognizes the impossibility of eliminating these market failures, and that it may be cheaper to reduce demand than to obtain new supplies. However, we must first establish that such market failures exist. What data prove (or even suggest) that energy conservation market failures exist?

## 1.4 Documenting Market Failures

Surprisingly little research has been conducted to document energy market failures on the demand side. Perhaps the most eloquent summary of the problem is by Blumstein et al.[28] Even there, the authors are forced to resort to anecdotal information rather than quantitative data. The absence of documentation may explain the great faith in deregulating energy prices as a cure for our energy problems. The remainder of this section will describe market failures related to energy conservation.

1.4a. Information Failures. Although it is generally accepted that consumers will make rational investment decisions if provided with adequate energy-related information, little data exist to either support or contradict this statement. Ideally we want controlled experiments showing how consumer response changes when information is provided. A home energy audit is one way of delivering this information. Unfortunately, few follow-up studies have been conducted to determine whether more conservation measures were implemented in audited homes.[29] In a Berkeley study, audited homes did not implement more measures than those unaudited.[30]

The new energy labels on American appliances provide a rich source of data for assessing changes in consumer behavior, yet no quantitative analysis of changes in consumer purchasing patterns has been done. A Canadian study [31] and anecdotal information suggest that appliance manufacturers are rapidly phasing out models at the higher end of the energy-use spectrum. This is presumably due to better-informed consumers shunning these inefficient models.

1.4b Asymmetric Discount Rates. The discount rates used in investment decisions are typically lower on the energy supply side than on the demand side. If energy suppliers could invest in conservation, they would use a lower discount rate, thus finding more measures attractive. This market failure is well described by Hatsopoulos et al.[32] Utilities typically use nominal rates below 20%, whereas consumers operate with rates well above this. In a study of air-conditioner purchases, Hausman found that consumers acted as if they used a 25% discount rate (and higher if they were poor).[33] For at least ten years, air conditioners have carried labels listing the Energy Efficiency Ratio (EER). In theory, this permits the consumer to make a life-cycle cost calculation. However, this (often quoted) study consisted of only 65 households and it was not clear whether the consumers had adequate information to make such a calculation.

O'Neal et al., have estimated the implicit discount rates in construction practices for single-family housing .[34] Here the discount rates varied from 6% to over 130% (in constant-dollars), depending on the assumptions regarding investment financing and fuel price escalation. Even then, the authors believed that consumer awareness and traditional building practice undermined the assumption that home-builders and buyers actually calculated the costs and benefits of conservation investments.

In another study, Whittier examined the purchase of several thousand energy-efficient refrigerators in the United States.[35] A national retailer offered two refrigerators having identical features except that one model consumed 350 kWh/year less electricity and cost $50 more. An influential consumer information magazine named the efficient model a "best buy" in 1977, and company executives believed that this recommendation increased its market share. Nevertheless, consumers consistently preferred the inefficient model. In 1977, the efficient model accounted for roughly 30% of sales, although this increased to 37% by 1979. To be indifferent between the two models, a consumer would have to operate with at least a 25 - 110% discount rate (the range depending on local electricity prices). These data suggest that more than half of the purchasers of these refrigerators used discount rates -- if they made any life-cycle costing decision at all -- above 25%.

During this time Massachusetts had in force a labeling law for refrigerators which appears to have influenced purchasing patterns. The efficient model was more popular in the New England region--the smallest area for which data are available, but Massachusetts is the most populous state in that region. In 1977, the efficient model accounted for 40% of sales, a share that increased to 77% in 1979. While the less efficient model was more popular nationwide, better-informed Massachusetts residents favored the efficient model. Improved information (and higher electricity prices) clearly play a role in consumer decisions.

Canada has had appliance labels since 1979. The Canadian Department of Consumer and Corporate Affairs claims that appliance labeling, combined with other information programs, caused a shift in consumer purchasing patterns resulting in as much as a 33% upgrading in efficiency.[36]

1.4c An Amortization Time Shorter than the Physical Lifetime. If permitted to invest in conservation, a utility would judge some investments profitable that consumers would reject because the utility can amortize the investments over a longer time period. This would lower the cost of energy-related services. In contrast, consumers often amortize an investment over a period shorter than its working lifetime because they cannot rely on recouping an energy-efficiency premium upon resale. This will certainly remain the case for refrigerators, where even an expert cannot recognize an efficient model. In the auto market, prices of used gas-guzzlers are discounted, and models having good fuel economy command a premium. Again, poor information may be an important element, yet it is difficult to pinpoint how important.

1.4d Separation of Costs and Savings. Many conservation measures require investments by persons or institutions that will not realize the savings. If a tenant pays the utility bills, for instance, then the landlord does not benefit from investments in energy conservation. (In a perfect market, the rent would reflect energy efficiency; in practice, few prospective tenants could recognize an efficient rental unit.) About 35% of all homes are renter-occupied.[37] The proportions for commercial and industrial properties are less meaningful owing to the use of long-term leases and special arrangements.

About half of all residential appliances are purchased by persons who will not be responsible for their energy consumption. This includes landlords and contractors building new houses. General Electric, for example, sells 40% of its major appliances to home builders.[38] Furthermore, a study of appliances in new home construction found the builders paid little attention to energy efficiency: "... about 60% of all such brand/model choices are made without consideration for the energy efficiency of the appliance or HVAC equipment. Of the remaining 40%, about three quarters give secondary consideration to energy efficiency, and the remaining quarter rate energy efficiency as a primary consideration."[39]

Both new home builders and landlords usually seek the cheapest possible appliance that will not detract from the attractiveness of the home. The cheapest is generally the least efficient model, too. We can infer that appliances, accounting for about 50% of the residential sector's total energy use (and an unknown fraction of the commercial and industrial sector's use), are excluded from any life-cycle costing due to the separation of investor and benefactor. Higher energy prices will force these "captive" consumers to reduce energy consumption through belt-tightening or "sacrifice" rather than through cost-effective technological improvements.

No matter who is paying the bill, energy prices do not fully reflect their costs. Residential customers do not pay extra for peak electric power, even though it is more expensive to generate. Instead, these additional costs are distributed among all customers. Time-of-use pricing might lead to conservation of peak power.[40] Similarly, the costs of maintaining military forces in readiness for possible use in the Middle East are not included in the price of oil. These costs are distributed among all taxpayers. An oil-security surcharge imposed on imported oil would induce additional conservation and reduce the nation's vulnerability to supply interruptions.

1.4e Risk Aversion. Even though we can accurately predict the average energy savings (over a stock) for a measure, the actual savings for a particular case will probably differ from that average. Small variations in local operating conditions or quality of installation make the exact savings impossible to predict. If the variance of potential savings is sufficiently large, a risk-averse consumer will prefer a more secure investment, even with lower returns, to the conservation measure.

Planners of large-scale conservation programs can ignore the variations in energy savings. They minimize risk by implementing the measure several thousand times; they may assume with confidence that they will achieve an average energy savings very close to that predicted. Given this lower risk, a single consumer might have chosen the conservation measure over the alternative. Unfortunately, consumers cannot obtain "conservation insurance;" no institutional means exist for them to reduce their risk.

It is difficult to gauge the size of this market failure. Wide variations in energy savings from a measure are extremely common. Yet little is known regarding the risk aversion of consumers. We cannot predict the extent that uncertainty deters consumers from implementing conservation measures. Nevertheless, the perspective adopted by a utility will certainly differ from that of consumers and will mean that a conservation measure that is economically attractive to a utility may be unacceptable to a consumer.

The energy marketplace is not unique in having market failures; indeed, the water market may be even more riddled. However, the dollar magnitude of the failures is greater with energy. Roughly 40% of all new plant and equipment expenditures in the U.S. are invested in the energy-supply sector.[41] There is also an enormous divergence between current behavior and what appears to be economically optimal. Wright et al., for example, suggest that 30 - 80% (depending on the end use) could be saved if the market worked perfectly. Finally, the multiple layers of market failures appear to be unique in the energy sector; nearly every consumer in the energy marketplace is affected by one failure, and most consumers by many.

## 1.5 Limitations of Conservation Supply Curves

Even the best-researched supply curves of conserved energy will suffer from limitations of the data. There are also conceptual limitations that parallel other models. Both problems will be referred to throughout this paper.

Conservation supply curves overestimate the energy savings because a constant level of service is assumed. At higher energy prices, consumers will become more frugal, and shift to lower levels of energy-related services. A conservation measure often saves less energy at a lower level of service. By not accounting for this shift, the curves overestimate energy savings to an extent that depends on the consumers' price elasticity in relation to energy prices: the greater the elasticity, the greater the overestimate. On the other hand, market failures often limit price elasticity: for instance, if the landlord pays for the heating, tenants will not respond to higher fuel prices. In principle, a supply curve could be developed using different levels of service; in practice, it is simpler to assume that the current level of service is maintained.

Finally, supply curves of conserved energy are not single-point forecasts. They characterize a technical potential tied to current patterns of energy consumption. They can be "blind-sided" by the appearance of a new end use or a change in preferences.

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# Chapter 2: THE SUPPLY CURVE CONCEPT

# 2. THE SUPPLY CURVE CONCEPT

This chapter describes the concepts behind, and construction of, supply curves of conserved energy (which, to avoid wordiness, will also be called "conservation supply curves"). The discussion here focuses on the mechanics, terminology, and fundamental assumptions behind the curves. The question of who supplies the conserved energy is saved for chapters 3 and 6 because the mechanics are the same regardless of the perspective adopted.

## 2.1 The Supply Curve of Conserved Energy Is an Investment Schedule

We do not demand energy itself but the services for which energy is an input. Through conservation measures, we seek to reduce our consumption of energy when it is expensive and to accomplish this for the least possible cost. Conservation measures are typically discrete actions, so we need a technique to select the measures that provide the greatest energy savings for the lowest cost--that is, an investment schedule. The supply curve of conserved energy is an investment schedule; it shows the marginal energy savings and cost of each measure. Ranking conservation measures by increasing marginal cost tells us which measure to implement first, second, and so on, in order to save the most energy for the least cost.

Unfortunately, the marginal contribution of a conservation measure often depends on the prior implementation of other measures. For example, the savings from improving the efficiency of a refrigerator compressor will depend on the heat gains into the refrigerated space. Additional wall insulation -- another reasonable conservation measure -- will reduce those heat gains. We must therefore know if the walls have been insulated before calculating the energy savings from the improved compressor. Such interactive effects between conservation measures are common and greatly complicate the construction of conservation supply curves.

Energy helps provide services; we can reduce our energy requirements by accepting lower levels of these services. This is an unrealistic (and an uninformative) perspective on energy conservation. Instead, we shall examine only those actions that maintain the current level of services or production. For a home, this assumption means maintaining the indoor air temperature at a comfortable level; in a factory, it means maintaining the current level (and quality) of production. The constant level-of-service assumption rejects measures that entail sacrifice or belt-tightening.

Supply curves of conserved energy show the potential for reducing energy consumption. Therefore it is necessary to select a baseline from which to measure the reductions. This baseline is often the current energy consumption or an arbitrary amount, possibly reflecting anticipated changes in the level of service. Energy "supplied through conservation" corresponds to the amount saved from the baseline.

Supply curves of conserved energy fall into four groups. They differ with respect to number of end uses and scale. The simplest conservation supply curve describes the potential savings for one unit in one end use. A curve for the space-heating end use in an arbitrary house -- the "unit" -- fits this category. Such a curve is called a "micro, single end-use supply curve." Several end uses for a single unit can be combined on a conservation supply curve to produce a "micro supply curve." A micro supply curve of conserved energy for a specific office building would include measures to reduce energy consumption for heating, cooling, ventilation, and lighting. In general, a "micro curve" refers to a particular unit (and its present energy-related equipment) that we can point to.

A "macro supply curve" describes the conservation potential for many units, that is, a stock of refrigerators, houses, or cars. The "single end-use macro supply curve" is a collection of micro, single end-use supply curves. We might, for example, examine only the conservation measures pertaining to residential water heating in Ohio. A supply curve of conserved energy for lighting in all Holiday Inns also fits this category. The more general macro supply curve consists of several end uses. Supply curves of conserved energy for New York's residential sector, transportation, or all Holiday Inns contain many end uses. Curves for an entire sector are sometimes called "grand supply curves."

## 2.2 A Micro Supply Curve of Conserved Energy

Determining the baseline energy consumption is the first step in constructing any supply curve. An accurate estimate of the baseline consumption is necessary because the savings are calculated as deviations from this amount. There is frequently the opportunity to directly measure the consumption (assuming that is the baseline) because the micro curve refers to an identifiable building, vehicle, or factory. Ideally there should be a baseline for each end use (even if the eventual goal is a micro supply curve containing several end uses).

Next, a list of conservation measures appropriate to that unit is assembled. The energy savings are calculated for each measure, assuming it is implemented first. This information can come from a variety of sources: operating specifications, laboratory results, engineering calculations, or modeling. Combining the energy savings with other economic data permits calculation of the "cost of conserved energy." The cost of conserved energy, or "CCE," indicates a measure's marginal cost. (This will be discussed in detail in Chapter 4.) The measures are ranked in order of increasing cost of conserved energy.

We now assume that the cheapest measure, that is the one having the lowest cost of conserved energy, is implemented. The energy savings for the remaining measures are recalculated based on this lower energy use. Not all the energy savings will change -- this depends on the interdependence of the measures. Again, the measures are ranked in order of increasing cost of conserved energy. The measure having the lowest CCE is assumed to be implemented; this procedure is repeated until the list of measures is exhausted.

The resulting sequence of measures is the least-cost expansion of the set--that is, the optimal investment schedule. The trial-and-error process outlined above is equivalent to minimizing the total cost of the conservation measures,

$$\text{least-cost schedule} = \min \sum_{\text{all measures}} CCE_i \times E_i$$

where

$CCE_i$ = cost of conserved energy for measure i

$E_i$ = energy savings of measure i.

The minimization is complicated because both the cost of conserved energy and energy savings for measure 'i' may depend on other measures. The simplest way to find the minimum is through a process similar to the trial-and-error technique described earlier.[1]

The supply curve of conserved energy is a plot of the cumulative energy saved versus the cost of conserved energy. Each measure is represented by a step, the width of which is the energy saved and the height of which is the cost of conserved energy. The procedure outlined above ensures that the curve will be constantly rising. If the curve were smooth (instead of in steps), then the first derivative would be non-negative. The second derivative's sign would be either positive or negative and, furthermore, could change several times along the smooth curve.

The iterative procedure used to calculate the optimal order can be performed rapidly by a computer. Appendix 1 presents two computer programs to accomplish this task.[2] Both programs require that the energy savings for each measure be described by an equation. The values within the equation may be reset as other measures are implemented. One program was used in the following example.

## 2.3 A Hypothetical Example of a Micro Conservation Supply Curve

Consider a hypothetical house's demand for space heating. In a typical year it uses 150 GJ to provide a specific level of service, namely, an air temperature of 22$^{o}$C. The menu of possible conservation measures for this house is:

1. attic insulation
2. wall insulation
3. weatherstripping
4. intermittent ignition device for furnace
5. furnace tune-up
6. duct insulation.

The energy savings are calculated using the algorithms shown in Table 2-1. The initial conditions for this example are listed at the top of Table 2-2. The optimal order of conservation measures, using the logic

Variables:

| | | |
|---|---|---|
| attic-loss | = | attic conduction loss |
| wall-loss | = | wall conduction loss |
| infil-loss | = | infiltration loss |
| wind-loss | = | window conduction loss |
| pilot-loss | = | pilot light loss |
| $\eta_{furn}$ | = | furnace efficiency |
| $\eta_{duct}$ | = | duct efficiency |
| $\eta_{sys}$ | = | furnace system efficiency |
| t-stat | = | thermostat setting ($^{o}C$) |

1. attic insulation

$$\Delta E = \frac{1}{\eta_{sys}} (.8) \text{(attic-loss)}$$ resets: attic-loss

2. wall insulation

$$\Delta E = \frac{1}{\eta_{sys}} (.6) \text{(wall-loss)}$$ resets: wall-loss

3. weatherstripping

$$\Delta E = \frac{1}{\eta_{sys}} (.38) \text{(infil-loss)}$$ resets: infil-loss

4. intermittent ignition device

$$\Delta E = \text{pilot-loss}$$ resets: pilot-loss

Table 2-1. Algorithms used to calculate the energy savings from conservation measures used in the example. Note that an algorithm includes resetting values after calculation of energy savings. This simulates implementation of the measure and avoids double-counting energy savings in subsequent measures. Two additional measures, installation of a clock thermostat (to allow a thermostat setback) and installation of storm windows, are listed in the table but not used in this example. They will be used for analyses in Chapter 5.

5. furnace tune-up

$$\Delta E = \frac{1}{\eta_{duct}} \left( \frac{1}{\eta_{furn}} - \frac{1}{.75} \right) \text{(wall-loss + attic-loss + infil-loss + wind-loss)}$$

resets: $\eta_{furn}$, $\eta_{sys}$

6. duct insulation

$$\Delta E = \frac{1}{\eta_{furn}} \left( \frac{1}{\eta_{duct}} - \frac{1}{.96} \right) \text{(wall-loss + attic-loss + infil-loss + wind-loss)}$$

resets: $\eta_{duct}$, $\eta_{sys}$

7. storm windows

$$\Delta E = \frac{1}{\eta_{sys}} (.73) \text{(wind-loss)}$$

resets: wind-loss

8. thermostat setback

$$\Delta E = \left( \frac{2}{\text{t-stat} - (-3)} \right) \left( \frac{1}{\eta_{sys}} \right) \text{(wall-loss + attic-loss + infil-loss + wind-loss)}$$

resets: t-stat, wall-loss, attic-loss, infil-loss, wind-loss

Table 2-1. (Continued).

**initial conditions and assumptions:**

| | |
|---|---|
| energy use | = 150.3 (GJ/year) |
| thermostat setting | = 22.0 (deg. C) |
| attic conduction loss | = 20.0 (GJ/year) |
| wall conduction loss | = 35.0 (GJ/year) |
| infiltration loss | = 18.0 (GJ/year) |
| window loss | = 13.0 (GJ/year) |
| pilot loss | = 7.0 (GJ/year) |
| furnace syst.effic. | = 0.60 |
| discount rate | = 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 300.0 | 25.0 | 1.6 | 136.8 | 13.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.8 | 105.1 | 31.7 |
| 3. add attic insulation | 700.0 | 30.0 | 1.9 | 81.0 | 24.2 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 74.0 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 63.6 | 10.3 |
| 6. tuneup furnace | 65.0 | 3.0 | 4.7 | 58.6 | 5.1 |

**Final conditions after retrofit:**

| | |
|---|---|
| energy use | = 58.6 (GJ/year) |
| thermostat setting | = 22.0 (deg. C) |
| attic conduction loss | = 4.0 (GJ/year) |
| wall conduction loss | = 14.0 (GJ/year) |
| infiltration loss | = 11.2 (GJ/year) |
| window loss | = 13.0 (GJ/year) |
| pilot loss | = 0.0 (GJ/year) |
| furnace syst.effic. | = 0.72 |
| discount rate | = 5.0 % per year |

Table 2-2. Assumptions and calculations for a series of space-heating conservation measures applied to a hypothetical home. See Figure 2-1 for the associated supply curve of conserved energy. This example also serves as the case "with duct insulation" in the macro-supply curve of conserved energy.

described earlier, is also shown in Table 2-2. Figure 2-1 is the supply curve of conserved energy.

A conservation measure is cost-effective if its cost of conserved energy is less than the price of the energy that the measure displaces. If the price of fuel was $4/GJ, then measures having costs of conserved energy below that price would be cost-effective. Every measure except the furnace tuneup would be economical. An increase in energy prices will not change the supply curve, but it will raise the cut-off price. If fuel prices jumped to $5/GJ, then even the furnace tuneup measure would be cost-effective.

The maximum cumulative energy conserved represents the "reserves of conserved energy." The reserves of conserved energy available at costs of conserved energy below the cut-off price represent the "economical reserves of conserved energy."

## 2.4 A Macro Supply Curve of Conserved Energy

A macro supply curve of conserved energy describes the conservation potential for a stock of equipment rather than for a single unit. Constructing a macro, or aggregate, curve is more difficult than creating a micro curve because we have less detailed information about a stock than about a single unit. Some new complications are:

1) determining the initial conditions;
2) calculating the average energy savings for each measure;
3) determining the timing of the implementation; and
4) accounting for uncertainties in the stock.

The first step in constructing a macro supply curve is to select an end use and estimate its initial energy use. Knowing this initial energy use is not sufficient, however. Taking autos as an example, we must know whether gasoline consumption is high because the vehicles are driven long distances or because they are inefficient. Thus, the energy-related attributes of each end use must be determined. For autos, the attributes include distance driven and average fuel economy. Again, the initial energy use need not serve as the base case. Population growth, expected increased production, or an anticipated change in the level of service may justify selecting a different energy use. For example, if we expect consumers to drive more kilometers per year than presently, the conservation supply curve should be based on that higher level of service. After adjusting the initial energy use to reflect conditions, a menu of conservation measures is created. The average energy savings, cost, and lifetime for each measure is estimated. Average savings must be used here because the conservation data apply to a stock rather than a single unit as in the micro curves. From this, we can calculate the measure's cost of conserved energy.

There is a "heroic assumption" behind all macro supply curves of conserved energy -- namely, that we can accurately represent a diverse stock with a single "average" case. A measure's energy savings in the average case and for any single unit will probably differ, but the heroic assumption declares that these errors will cancel. Further, a measure's aggregate energy savings will be simply the product of the

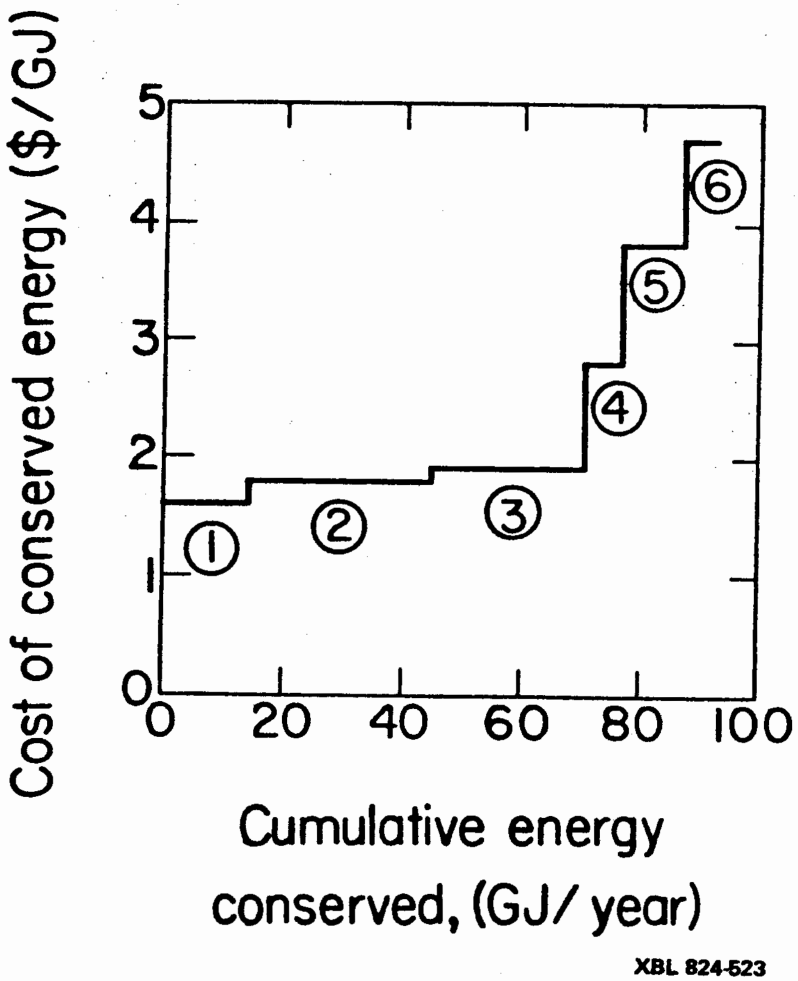


Figure 2-1. A micro supply curve of conserved energy for space heating. See Table 2-2 for assumptions and initial conditions.

average energy savings and the number of units to which the measure is applied. This aggregation problem, which one hopes does not introduce large errors, is discussed further in Chapter 5.

Some conservation measures will apply only to part of the stock. For example, the measure "reduce standby friction losses of auto air conditioning units" can only be applied to cars having air conditioners. We must therefore determine the eligible stock for each macro measure. The product of the average energy savings and the eligible stock yields the aggregate energy savings for the measure:

| | | | | |
|---|---|---|---|---|
| ultimate aggregate energy savings | = | average energy savings per unit | x | eligible stock |

No conservation measure can occur instantaneously, so we must also estimate the maximum rate at which the measure can be implemented on a regional scale. This is called the "penetration rate" and is an estimate of the highest implementation rate possible without raising the price through labor and materials bottlenecks. The ultimate conservation potential depends on the length of time we are willing to wait, that is, our "time horizon." The conservation potential of improvements in refrigerators is very sensitive to the time horizon. Since improvements in refrigerator efficiency must be made during their manufacture, these energy savings will occur only as existing refrigators are replaced. The stock of refrigerators turns over very slowly, about 1/20 per year. If the time horizon is short (for example 5 years), then only 1/4 of the ultimate potential will be realized. This can be expressed as

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| aggregate energy savings shown on supply curve | = | average energy savings per unit | x | eligible stock | x | penetration rate | x | time horizon . |

The aggregate energy savings (having already been adjusted for the eligible fraction of the stock and the time horizon) and the average cost of conserved energy represent one step on the macro supply curve of conserved energy.

## 2.5 An Example: A Macro Conservation Supply Curve for Residential Space Heating

Consider a hypothetical region consisting of 1000 homes that are quite similar in size and construction. Ordinarily, we would try to represent these homes with a single, average case and estimate the energy savings from various measures as we did for the micro case. Unfortunately, half of the homes were built with inaccessible ducts that could not be insulated. Duct insulation strongly influenced the energy savings of subsequent measures, so a second average house was constructed to represent this second group. The optimal sequence of measures and their respective energy savings are given in Table 2-3. It is identical to Table 2-2, except that duct insulation was deleted from the menu of acceptable measures.

initial conditions and assumptions:

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. add wall insulation | 900.0 | 30.0 | 1.7 | 115.3 | 35.0 |
| 2. add attic insulation | 700.0 | 30.0 | 1.7 | 88.6 | 26.7 |
| 3. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 81.6 | 7.0 |
| 4. weatherstrip | 300.0 | 10.0 | 3.4 | 70.2 | 11.4 |
| 5. tuneup furnace | 65.0 | 3.0 | 4.2 | 64.6 | 5.6 |

Final conditions after retrofit:

| | | |
|---|---|---|
| energy use | = | 64.6 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 4.0 (GJ/year) |
| wall conduction loss | = | 14.0 (GJ/year) |
| infiltration loss | = | 11.2 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.65 |
| discount rate | = | 5.0 % per year |

Table 2-3. Assumptions and calculations for a series of space-heating conservation measures applied to a hypothetical home where duct insulation is not a potential measure. This is the case of "no duct insulation" in the macro-supply curve of conserved energy.

A macro supply curve could be constructed to show the energy savings for all 11 measures but, since the measures are so similar, they are combined. Besides, a utility or government-sponsored insulation program would probably not distinguish between those homes with accessible duct insulation and those without. A new average energy savings must be calculated since the energy savings for the two stocks differ. The stock-weighted energy savings are listed in Table 2-4. Likewise, the cost of conserved energy must be recalculated to reflect the stock-weighted energy savings. This is the third column in Table 2-4.

These measures have different penetration rates. It is technically possible to tune up all the furnaces in one year, but insulating the walls of all the homes might take longer, perhaps 10 years. The conservation potential for short time horizons (that is, less than the penetration time) will be small because the conservation measures have not fully penetrated the stock. Tables 2-5a and 2-5b give the eligible fractions, penetration rates, and savings for two time horizons.

Figure 2-2 shows two macro supply curves of conserved energy. The width of each step represents the energy saved by the measure (assuming the technical potential was realized). A step's height represents the average cost of conserved energy for implementing that measure in all eligible homes. Once again, the end of the curve shows the total reserves of conserved energy. The price of the displaced energy establishes the economic reserves of conserved energy. The left curve assumes a one-year time horizon; the right curve assumes a ten-year time horizon. The curve for a ten-year horizon is not simply ten times the one-year curve because the penetration rates vary among measures.

These supply curves display the technical potential and are not forecasts. They serve as a starting point for discussions and as a means of focusing efforts on conserving the greatest possible amount of energy for the lowest cost. Other purposes of the supply curves are discussed in the next chapter.

**Initial conditions and assumptions:**

| | | |
|---|---|---|
| average energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Cumulative Savings | Measure Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 300.0 | 25.0 | 1.6 | 13.4 | 13.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.8 | 46.8 | 33.4 |
| 3. add attic insulation | 700.0 | 30.0 | 1.9 | 71.3 | 24.5 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 78.3 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 89.1 | 10.8 |
| 6. tuneup furnace | 65.0 | 3.0 | 4.7 | 94.5 | 5.35 |

**Final conditions after retrofit:**

| | | | | |
|---|---|---|---|---|
| ** | average energy use | = | 61.6 (GJ/year) | *** |
| | thermostat setting | = | 22.0 (deg. C) | |
| | attic conduction loss | = | 4.0 (GJ/year) | |
| | wall conduction loss | = | 14.0 (GJ/year) | |
| | infiltration loss | = | 11.2 (GJ/year) | |
| | window loss | = | 13.0 (GJ/year) | |
| | pilot loss | = | 0.0 (GJ/year) | |
| ** | avg furn. syst.effic. | = | 0.685 | *** |
| | discount rate | = | 5.0 % per year | |

Table 2-4. Assumptions and calculations for a series of space-heating conservation measures for the average home. The energy savings are stock-weighted to reflect those homes eligible for duct insulation. The cost of conserved energy (CCE) is based on the average energy savings. The final conditions reflect average conditions in the entire stock.

| measure | average energy savings | penetration rate (per year) | eligible fraction of stock | aggreg. savings * 1-year | 10-year |
|---|---|---|---|---|---|
| 1. duct insulation | 13.4 | .2 | 0.5 | 1340 | 6700 |
| 2. wall insulation | 33.4 | .15 | 1. | 5010 | 33400 |
| 3. attic insulation | 25.5 | .2 | 1. | 5100 | 25500 |
| 4. intermittent ignition device | 7. | .5 | 1. | 3500 | 7000 |
| 5. weatherstrip | 10.8 | .25 | 1. | 2700 | 10800 |
| 6. furnace tuneup | 5.4 | 1. | 1. | 5400 | 5400 |

* For time horizon x penetration rate < 1:

aggregate savings = average savings x penetration rate x total stock x eligible fraction x time horizon

For time horizon x penetration rate >= 1:

aggregate savings = average savings x total stock x eligible fraction

| measure | average CCE ($/GJ) | cumulative energy savings 1-year horizon | 10-year horizon |
|---|---|---|---|
| 1. duct insulation | 1.6 | 1340 | 6700 |
| 2. wall insulation | 1.75 | 6350 | 40100 |
| 3. attic insulation | 1.79 | 11450 | 65600 |
| 4. intermittent ignition device | 2.80 | 17650 | 72600 |
| 5. weatherstrip | 3.61 | 20350 | 83400 |
| 6. furnace tuneup | 4.45 | 25750 | 88800 |

Table 2-5a and b. Table 2-5a (top) shows assumptions regarding the stock and penetration of conservation measures. Note that the stock is 1000 homes. Table 2-5b (bottom) is the supply curve table for Figure 5-2. The CCE's come from Table 2-4 and the aggregate energy savings from Table 2-5a.

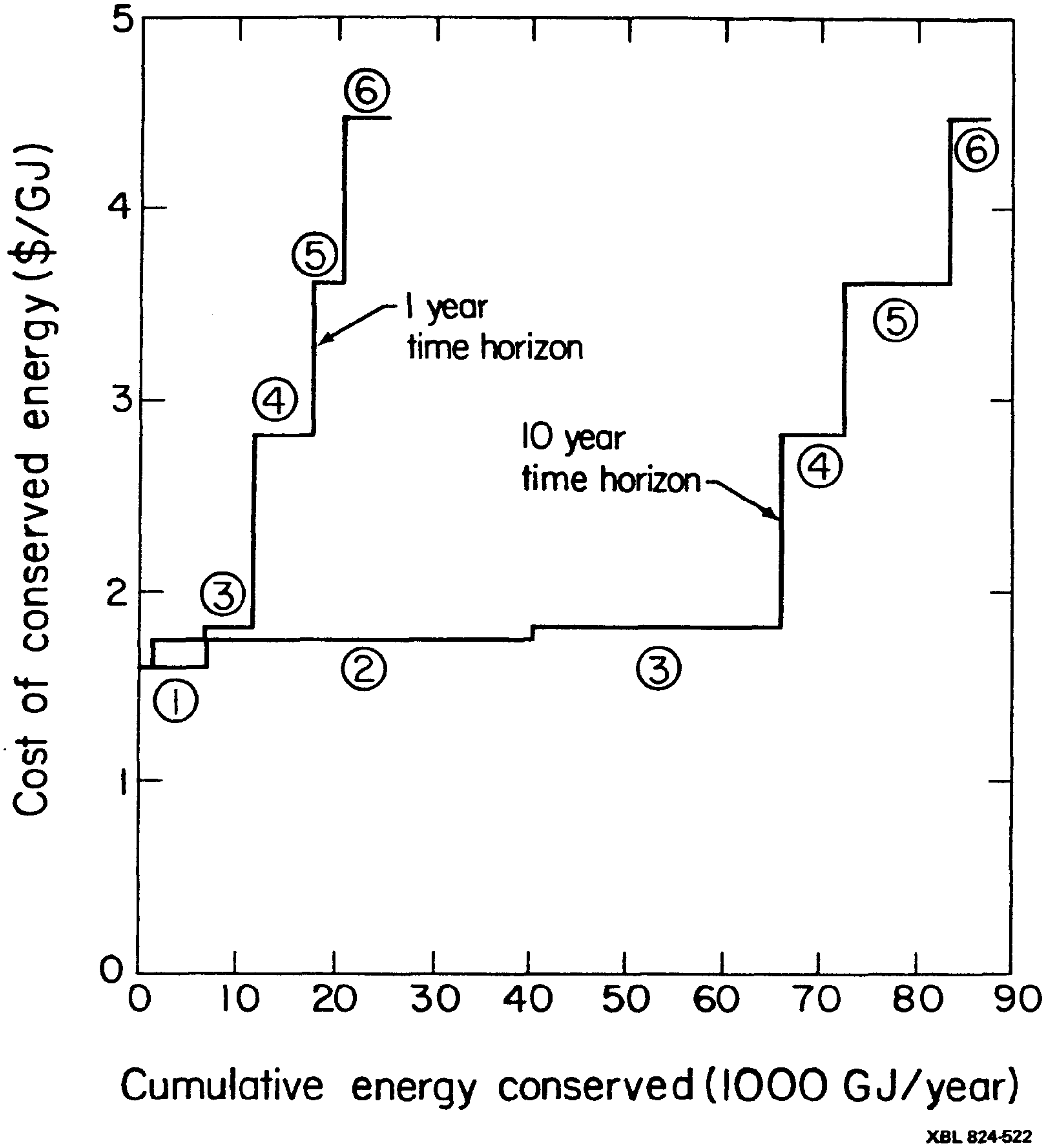


Figure 2-2. A macro supply curve of conserved energy for space heating. The left-hand curve is based on a 1-year time horizon. The right-hand curve is based on a 10-year horizon. Note that the curve for the 10-year horizon is not simply ten times the 1-year curve because the penetration rates vary among the measures. See Tables 2-4, 2-5a, and 2-5b for assumptions.

## 2.6 References and Notes

1. The sequences are usually less than a dozen measures, so a computer can perform the trial-and-error technique quite rapidly. More efficient sorting techniques could be used for longer sequences.

2. The first program, in the UNIX language 'C', was written by Alan Meier, with the assistance of James Reeds. The second program, in FORTRAN, was written by Wolfgang Lührsen. It is based on the original 'C' program. All output presented here is from the 'C' program.

# Chapter 3: THE ROLE OF CONSERVATION SUPPLY CURVES

# 3. THE ROLE OF CONSERVATION SUPPLY CURVES

Supply curves of conserved energy are tools for better understanding how we use energy and for developing energy policy. They provide information not easily obtained from other types of analysis. This chapter discusses features of the curves which have policy implications. Examples of each feature are drawn from the supply curve of conserved electricity developed in a California study (Figure 3-1 and Table 3-1).[1] Some of the practical problems associated with using these curves are discussed in later chapters.

## 3.1 The Curves Show Which Conservation Measures Are Significant

On a supply curve, potentially important measures appear as broader steps. The curves show the significance of a measure with respect to both total energy use and other conservation measures. This addresses an early conservation policy question: what measures will save large amounts of energy? Figure 3-1 reveals that replacing all refrigerators with models conforming to the California Energy Commission standard would potentially save about 1.5 % of current residential electrical use. In addition, this measure would save three times more electricity than would insulating electric water heaters.

Of course the technical potential may not be fully realized for either measure. Institutional obstacles may make implementation of a less significant measure easier. With a determined effort, we could insulate all the water heaters in a year. On the other hand, the turnover of refrigerators is slow, so this reserve of conserved energy cannot be tapped quickly.

## 3.2 The Curves Show Which Conservation Measures Are Cost-Effective

On a curve, the most economically attractive measures appear earliest, that is, to the lower left. The cost-of-conserved-energy framework uses consistent accounting procedures for all measures, so measures will have low CCEs for similar--and understood--reasons. This feature of the supply curve addresses the often-raised question: which conservation measures should be performed first? Focus clearly should be on the leftmost measures of the curve.

A measure can also be "cheap" relative to the energy it displaces. This, too, is clearly displayed, when the cost of conserved energy is less than the price of the energy it displaces. For example, insulating the ceilings of uninsulated electrically heated homes has a cost of conserved energy of 3.7 cents/kWh. This is much less than the 8 cents/kWh consumers must pay for the heat presently lost through ceilings.

## 3.3 The Curves Show the Potential for Conservation in a Consistent Manner

A consistent accounting technique, with respect to both costs and energy, creates curves that permit meaningful comparisons of energy-conservation measures. The user may address a more sophisticated

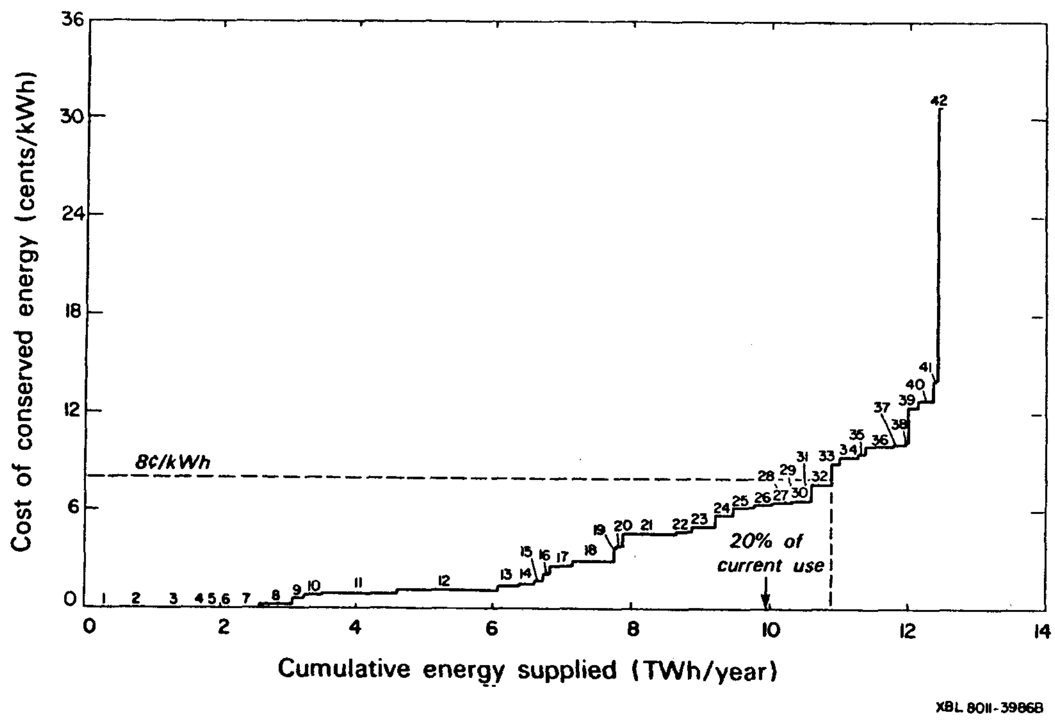


Figure 3-1. The grand supply curve of conserved electricity for California's residential sector. All major residential electrical end-uses have been combined on this curve. Each step corresponds to a conservation measure: the y-coordinate is the cost of conserved energy and the x-coordinate is the cumulative electricity saved (per year). The measures are listed in Table 3-1. A 5% discount rate was used. These are the savings after 10 years. The cumulative electricity saved after the final measure corresponds to about 25% of the total electricity used in California's residential sector. This energy is roughly equivalent to the output of two standard 1000 MW power plants. Adapted from Wright et al.

| Measure | Cost of conserved energy (cents/kWh) | Energy supplied per measure (GWh/yr) | Cumulative energy supplied (TWh/yr) |
|---|---|---|---|
| 1. Solid-state color TV | 0. | 599 | 0.6 |
| 2. Solid-state black-and-white TV | 0. | 322 | 0.9 |
| 3. CEC standard refrigerator | 0. | 728 | 1.6 |
| 4. CEC standard room air conditioner | 0. | 152 | 1.8 |
| 5. CEC standard central air conditioner | 0. | 168 | 2.0 |
| 6. Water heater thermostat setback | 0. | 186 | 2.2 |
| 7. Cold-water laundry | 0. | 407 | 2.6 |
| 8. Low-flow showerhead | 0.2 | 497 | 3.1 |
| 9. Night setback of 10°F | 0.6 | 153 | 3.2 |
| 10. Pool filter savings from cover | 0.8 | 287 | 3.5 |
| 11. Buy most efficient refrigerator | 0.9 | 1,092 | 4.6 |
| 12. Refrigerator package "A" | 1.1 | 1,466 | 6.1 |
| 13. Buy most efficient freezer | 1.4 | 306 | 6.4 |
| 14. Water heater insul. blanket | 1.5 | 241 | 6.6 |
| 15. 3-Way bulb to high efficiency | 1.7 | 111 | 6.7 |
| 16. Seal attic bypasses | 2.1 | 93 | 6.8 |
| 17. Freezer package | 2.6 | 328 | 7.1 |
| 18. Kitchen fluorescent | 2.9 | 609 | 7.7 |
| 19. Install R-19 in ceiling | 3.7 | 10 | 7.8 |
| 20. Divert elec. clothes dryer vent | 3.8 | 105 | 7.9 |
| 21. Switch to gas clothes dryer | 4.6 | 767 | 8.6 |
| 22. Exterior fluorescent conversion | 4.7 | 239 | 8.9 |
| 23. 100 W bulb to fluorescent (high use light) | 5.0 | 335 | 9.2 |
| 24. Storm windows | 5.7 | 258 | 9.5 |
| 25. Wall insulation air conditioning savings | 6.2 | 309 | 9.8 |
| 26. Buy most efficient central air conditioner | 6.4 | 252 | 10.0 |
| 27. Manual refrigerator improvement | 6.5 | 208 | 10.2 |
| 28. Buy most efficient electric dryer | 6.5 | 62 | 10.3 |
| 29. Fireplace damper | 6.5 | 13 | 10.3 |
| 30. 100 W bulb to fluorescent (medium use light) | 6.6 | 290 | 10.6 |
| 31. Install R-11 in walls | 7.4 | 9 | 10.6 |
| 32. 3-way bulb to fluorescent | 7.6 | 305 | 10.9 |
| 33. Caulking | 8.9 | 102 | 11.0 |
| 34. Switch to gas range | 9.3 | 274 | 11.3 |
| 35. Window shading for centrally air conditioned homes | 9.5 | 95 | 11.4 |
| 36. Refrigerator package "B" | 10.0 | 406 | 11.8 |
| 37. 100 W bulb to fluorescent (low use light) | 10.1 | 191 | 12.0 |
| 38. Buy most efficient room air conditioner | 10.2 | 24 | 12.0 |
| 39. 75 W bulb to fluorescent | 12.4 | 156 | 12.2 |
| 40. Weatherize apartments | 12.8 | 204 | 12.4 |
| 41. Additional R-19 in ceiling | 14.0 | 69 | 12.4 |
| 42. Weatherstrip | 30.8 | 48 | 12.5 |

Table 3-1. Table to supplement the grand supply curve of conserved electricity (Figure 3-1). The conservation measures are listed in the order they appear on the curve. Measures 1 and 2 refer to the replacement of existing tube-operated televisions with solid state models. This will occur without any intervention. The "CEC standard" measures mean replacing the existing appliance (when it wears out) with one meeting the California Energy Commission standards. The "Buy most efficient" measures mean replacing the existing apppliance (when it wears out) with the most efficient available. The refrigerator and freezer "package" and "improvement" measures refer to a series of conservation measures outlined in reports by Arthur D. Little Inc. See Wright et al., for detailed explanations of the measures.

policy dilemma: has this energy already been saved by an earlier measure? There is no double-counting of energy savings; the reply is always "no" (although a cheaper measure may have conserved a major part of a proposed measure's potential).

Further interpretations of the data are possible because of the methodology used to produce the curves. We can, for example, reliably predict the consequences of implementing a measure earlier than shown on the curve. This might be necessary if certain measures are rejected as unfeasible because they are capital-intensive. Eliminating measures (for whatever reason) moves subsequent measures forward in the sequence. The actual energy savings will either remain the same or increase. Likewise, the cost of conserved energy will decrease. So, even though the supply curves apply to a specific order of events, that is, a sequence of conservation measures, the consistent methodology permits application of the results to other conditions.

A state legislator proposed that weatherstripping, along with a number of other conservation measures, be required in all California homes prior to resale.[2] An opponent noted that, on the supply curve, weatherstripping is clearly uneconomical at 30.8 cents/kWh; he sought to delete the measure. A legislative aide responded that many non-mandatory measures precede weatherstripping on the supply curve (viz., thermostat set-back, sealing ducts, insulation and sealing of by-passes). If weatherstripping were implemented before these major measures, its energy savings would be much greater, and cost of conserved energy much lower, than shown on the curve. (Still, the aide could not be certain that weatherstripping would be cost-effective, but the economics would certainly be better.) The aide expressed a willingness to delete weatherstripping in favor of measures that appear earlier in the sequence, but feared enforcement would be excessively complicated, and therefore preferred weatherstripping.

## 3.4 The Curves Permit Comparison of Costs of Conservation to Those of New Supplies

The potential for new energy supplies is often presented in the form of supply curves. Expressing the conservation potential in a similar framework puts conservation on comparable basis, both with respect to characterizing the investment criteria of the output (i.e., energy available per year and cost per unit of energy). The conservation supply curve explicitly treats the often thorny issues of timing and a varying discount rate. The curves also hold the level of service constant, which permits a policy-maker to assume that the consumer will be indifferent between conserved energy and that supplied by a utility.

We will examine a hypothetical situation to see how the curves might be used. A new power plant is required in California to replace a retired facility (that is, to meet existing electrical demand). The capital costs for the new plant are estimated to be at least 8 cents/kWh, and the total costs to be at least 11 cents/kWh. It would take at least 10 years to build the plant, and the utility expects to borrow capital at a 5% real annual rate. On the other hand, the supply curve of conserved electricity indicates that roughly two power plant's equivalent output could be conserved at CCEs below 8 cents/kWh, using a 10-year time horizon and a 5% discount rate. The conservation alternative should be seriously considered.

The comparison is not perfect, however, due to differences in timing of the energy supplies. Since the electricity savings will probably be unevenly distributed over the year, some peaking units may still be needed. Nevertheless, the expensive baseload plants could be avoided. Second, conserved energy is phased in gradually, as conservation measures are implemented and as appliances and equipment are slowly replaced. Yet this conserved energy begins appearing immediately, whereas a power plant will make no contribution until its completion.[3]

## 3.5 The Curves Indicate Energy Market Failures

Most conservation supply curves show large reserves of conserved energy at costs well below the current energy price. Some of this potential is obviously due to lags in market response to higher energy prices, but most is due to various forms of market failure. These market failures were listed in Chapter 1.

The supply curves reveal the size (in energy terms) of market failures, and insights into the reasons for the failures. The larger the reserve of conserved energy below the current price, the larger the market failure. An inspection of individual conservation measures in that region may provide some clue to the form of market failure. For example, measure 11 in Figure 3-1 is "Buy most efficient refrigerator." Alone it saves 2% of current electricity use (4% over 20 years) at a cost of conserved electricity below 1.0 cents/kWh. Closer investigation would show that, until labels were introduced, consumers had no way of knowing the energy efficiency of a refrigerator. Clearly, we must provide the consumer with improved information. Next, we must observe purchasing patterns for new refrigerators. Are the labels sufficient to change purchasing habits, or does that address only part of the problem? Further research may be needed. The supply curves do not provide all the answers, but they do show where to begin looking.

## 3.6 The Curves Show How Far from Optimal our Energy Use Is

Traditional economic analysis approaches the issue of optimal energy use obliquely, often with assumptions that make any conclusions very shaky. We can compare current energy productivity to historical levels, or to those of other countries.[4,5] European countries generally produce more goods per unit of energy than the United States. At the same time, European energy prices are higher, so both the U.S. and Europe could be operating at economically optimal levels of energy consumption.

Such analyses cannot deal with the questions: how much additional investment in conservation would be cost-effective? what is the "least-cost" solution to meeting our energy-related needs? To find answers to these questions, we must perform engineering-economic analyses of conservation measures within every end use. The supply curve of conserved energy (and the accounting methodology behind it) is an ideal tool for this sort of analysis. The energy "gap" between optimal and current use is clearly displayed as the amount of energy that can be supplied through conservation below current energy prices. Similarly, the price "gap" (between the current energy price and the CCE of the measures on the curve) indicates the severity of the gap.

The above discussion ignores the secondary consequences of energy conservation and supply. These are discussed in Chapter 6. However, these result in only small adjustments to the conclusions presented above.

## 3.7 Conservation Supply Curves Show Potentials, and Are Not Forecasts

It is tempting to compare an energy demand forecast to a potentials study. Some comparisons can be made, but it is perhaps best to think of the analyses as complementary. Each begins with different assumptions and examines energy use from a different perspective. The conservation supply curves treat energy and efficiency measures as the major inputs to providing specific goods and amenities to consumers. Here the goal is to understand the extent and economics of substituting efficiency measures for energy consumption. In contrast, the role of a forecast is to predict future energy use given certain economic conditions. Forecasts tell us nothing about a change in levels of services that may take place. Likewise, energy price elasticity has no role in conservation supply curves. Conservation supply curves neither predict future energy use nor take into account changing economic conditions.

The chief complementary feature of forecasts and conservation supply curves is in helping us understand the elements of future energy demand. A potentials study establishes a lower envelope of technically plausible future energy consumption. In this case, the envelope is the energy consumption assuming all cost-effective conservation measures are implemented. This would be the energy use "if the market worked perfectly" and consumers maintained their original level of goods and services. Obviously other, still lower envelopes exist; a nuclear holocaust or deep recession would certainly lower energy demand. Yet we instinctively reject those sorts of situations as unlikely or at least not instructive as lower envelopes. So we add a constraint, namely that the level of services will remain constant during the period of analysis. Both practical and theoretical problems make the assumption of a constant level of service almost a necessity. (These are discussed in Chapter 6.)

Traditional models for forecasting are poorly suited for extracting specific energy-conservation policies. They rely on historical relationships and assumptions between exogenous factors, such as population growth, level of economic activity, energy prices, price and income elasticities, and energy consumption. Only the broadest sorts of energy-conservation policies can be proposed, such as "lower the birth rate" or "increase energy prices." Even these must be treated cautiously because the historical relationships may no longer hold. Note that the models do not fix the level of service; they change to an unknown extent behind the price-elasticity variable.

Supply curves of conserved energy provide the detail to support the general policy "improve energy productivity." The curves show precisely where energy productivity can be raised and what measures must be implemented in order to raise it. In this way, broad policy can be converted to detailed programs. However, this detail comes at a cost: the potential cannot be directly compared to forecasted energy use. Several assumptions used to construct the supply curves would lead to double-counting of energy savings.

In a forecast, the contribution from price elasticity includes both "belt-tightening" (due to higher energy prices) and substitution, that is, energy-conservation measures. In addition--although this aspect is often not discussed--the elasticity also includes shifts of consumer activity into less energy-intensive goods (switching from recreational vehicles to home computers), that is, a change in preferences. Belt-tightening and changing preferences save energy that might otherwise have been saved through investment in conservation measures. A potentials study does not include these effects. Put another way, forecasts must include energy savings through reductions and changes in services that are not included in a potentials study. Most forecasts do not explicitly list the conservation measures that will be implemented, so some measures may occur in both a potentials study and a forecast. As a result, the potentials cannot be directly subtracted from forecasts.

## 3.8 References and Notes


1. Janice Wright et al., "Supplying Energy Through Greater Efficiency: The Potential for Conservation in California's Residential Sector" (Berkeley, CA: Lawrence Berkeley Laboratory Report LBL-10738 [January 1981]).

2. California State Assembly Bill No. 2030. (1980).

3. In a recent seminar at the University of California, Berkeley, Amory Lovins claimed that it was cheaper to invest in conservation than pay the operating costs for Diablo Canyon (a controversial nuclear power plant nearly completed). Operating costs included those for fuel, decommissioning, radioactive waste disposal, and labor. Put in the terminology of the supply curve (his research relied heavily on the supply curves estimated by Wright et al.), the reserves of conserved electricity exceeded Diablo Canyon's output, and their CCEs were less than the plant's operating cost (per kWh). In this peculiar case, the power plant could be started immediately, whereas conservation would be phased in gradually. In the meantime, while waiting for the conserved electricity to come "on-line," the utility would be forced to purchase electricity from other sources. Brian O'Regan has investigated Lovins' assertion, and found that sufficient reserves of conserved electricity existed, at CCEs below Diablo Canyon's operating cost, to offset the plant's output. However, the cost of buying electricity elsewhere was an important, possibly determining, cost. If very cheap electricity could be purchased, then Lovins' assertion was correct. At higher (and more likely) electricity prices, the conservation alternative to Diablo Canyon would be more expensive. (Brian O'Regan, Lawrence Berkeley Laboratory, personal communication, March 3, 1982.)

4. Darmstadter, Joel; Dunkerley, Joy and Altman, Jack. How Industrial Societies Use Energy. Baltimore: Johns Hopkins University Press, 1977.

5. Lee Schipper and Allan J. Lichtenberg, "Efficient Energy Use and Well-Being: The Swedish Example", Science 194, 1001-1013 (1976).

# Chapter 4: THE COST OF CONSERVED ENERGY AS AN INVESTMENT STATISTIC

# 4 THE COST OF CONSERVED ENERGY AS AN INVESTMENT STATISTIC

The cost of conserved energy (CCE) has rapidly gained acceptance as a statistic for measuring the quality of energy-conservation investments. How should the cost of conserved energy be applied and what are the assumptions behind it? What advantages does it offer compared to other, more traditional investment statistics?

## 4.1 Traditional Investment Statistics

Many statistics already exist to measure the quality of an investment in energy conservation. These include net present value (NPV), benefit/cost ratio, return on investment (ROI), payback time, and internal rate of return (IRR). All of these are variations on life-cycle costing; they all transform information regarding cost of the measure, its lifetime and energy savings, energy prices plus assumptions regarding energy price escalation and discount rates, into a single investment statistic. They differ in the way they treat energy prices and discount rates. The question, "Is this a good investment?" is also answered differently. All cost-benefit textbooks discuss these techniques, although not necessarily as they apply to energy decisions.[1] Finally, some of the investment statistics yield results that are intuitively easy to grasp, that is, to recognize as a good or bad investment. These techniques are briefly reviewed below in the context of energy-conservation investments.

Calculating the net present value of a conservation investment requires the knowledge (or assumption ) of a discount rate and a fuel escalation rate. The result is a net present value--an absolute number of dollars. It is most useful when one must choose between several measures, all of which have the same initial cost; the measure having the highest NPV is the best investment. Here our decision is based on the rule, "Choose the investment having the highest net present value." However, the NPV technique cannot distinguish between a small investment having a rapid return and a large investment having a slow return if both have equal net present values. Thus, the NPV technique is best suited to comparing conservation investments with equal costs.

The benefit/cost ratio avoids the absolute nature of the NPV by calculating the ratio of the present value of the benefits to the present value of costs. Now the decision is based on the rule, "Choose the investment having the highest benefit-to-cost ratio." We can now compare investments having widely differing costs. We still must assume a discount rate and fuel price escalation rate. Finally, we do not have an intuitive grasp of a "good" benefit/cost ratio. Obviously it should be greater than one, but should it be 1.05 or 20?

The return on investment (ROI) statistic presents the ratio of annual energy savings (expressed in dollars) to the total investment. This is calculated with varying degrees of complexity. Sometimes the value of the first year's energy savings is inserted, even though a levelized value may be more appropriate (especially if fuel prices will escalate during the investment's lifetime). We can readily compare this number to other, familiar investments, such as the interest earned on a bank deposit. Our decision is based on the rule, "Choose the investment having the highest return on investment but reject those having returns less than that available in a savings account." Again, we must make assumptions about fuel price escalation and discount rate before calculating the ROI.

The payback period also offers a simple measure of investment quality. Our rule here is, "Choose the investment having the shortest payback time and reject any having a payback time greater than that available from a savings account." Not surprisingly, payback time is used only for the crudest analyses. One drawback of payback time is that it tells us nothing about conditions after the payback time has passed. For example, two investments having identical payback times may have vastly different salvage values. Obviously the measure having the higher salvage value should be more attractive, yet the payback time does not reflect this. The payback time does not provide full life-cycle costing.

The internal rate of return (IRR) requires only an assumption of fuel price escalation. Here, the rule is, "Choose the investment having the highest internal rate of return and reject any having IRRs less than some number." The IRR cut-off will be determined by whatever is available from alternative investments having equal risk.

One statistic peculiar to energy investments, which is occasionally used, is the ratio of a measure's cost to the energy saved in the first year:

$$\text{"X"} = \frac{\text{cost of measure (\$)}}{\text{first-year energy savings (i.e., GJ)}}$$

The energy savings are expressed in any convenient dimension, that is, kilowatt-hours, Btus, or barrels of oil. The great advantage of this statistic is the absence of any assumptions about energy prices. This statistic, while simple, fails to reflect differences in measures' lifetimes, the effects of fuel price escalation, or the differences among energy types. Worse, there is little intuitive feeling for a "good" conservation measure or how it compares to investments in other sectors.

Unlike other investments, the sole alternative to implementing a conservation measure is consuming (and paying for) energy. None of the above techniques easily addresses the question, "How does this conservation investment compare to those for alternative supplies?" In some cases, the "other investments" will be for developing energy supplies; in others, the alternative is purchasing energy directly. In either case, we have no intuitive notion of adequate (or good) net present values, returns on investment, and so on.

## 4.2 The Cost of Conserved Energy

The cost of conserved energy shares some of the advantages and drawbacks of the traditional techniques but also has unique features. Using the measure's cost, lifetime, annual energy savings, and assumed discount rate, we can calculate a cost of conserved energy:

$$CCE = \frac{I}{E} \; \frac{d}{1 - (1+d)^{-n}}$$

where

I = conservation investment
E = annual energy savings
n = lifetime
d = discount rate

The rule that governs our decision is now, "Choose conservation investments having the lowest cost of conserved energy, but reject any for which the cost of conserved energy exceeds the price of the energy it displaces." This is intuitively simple because the price of energy is known, as is the meaning of a "high" or "low" cost of conserved energy.

The price of energy does not enter the cost of conserved energy; rather, that price serves as a scale, or benchmark, against which one judges the cost of conserved energy. Independence from energy prices is particularly desirable when the most volatile element of the conservation investment decision is energy prices. For example, if the federal government imposed a surcharge on oil imports, ROIs, IRRs, present values, etc., would have to be revised to reflect the higher oil prices. In contrast, the cost of conserved energy remains constant. Of course, the comparison price does change, but comparison is preferable to recalculation.

The independence of the CCE from energy prices simplifies the analysis of conservation measures for many mass-produced items. Consider fuel economy measures for autos (in which the CCEs will be expressed as "cost of conserved gasoline," in dollars per liter). We need calculate only one set of CCEs because autos are centrally manufactured and similarly operated nationwide. This is a reasonable assumption because the principal determinant of fuel economy is the proportion of city to highway driving, not geography. The list of cost-effective measures will change depending on local gasoline prices.

The CCE is especially useful for comparing investments in conservation to investments in new supplies. Both are expressed in similar units, that is, cost per unit of energy. A utility, for example, would compare the cost of electricity from a new power plant to that of conserving electricity. The cost of generating a kilowatt-hour is a standard calculation in the planning process. Here, though, the cost of conserving a kilowatt-hour would also be calculated. With this information, the utility could choose the least-cost alternative. A mixture is also possible; namely, the cheaper conservation measures and a smaller power plant.

The cost-of-conserved-energy technique complements other investment statistics. Its hidden assumption is a uniform discount rate; its public assumption is the energy price. The NPV, benefit/cost ratio, and ROI calculations bury both the discount rate and future energy price assumptions. The IRR also hides speculations as to energy price, but explicitly shows the discount rate.

In spite of the CCE's increasing acceptance as an investment statistic, two features have remained murky, and mostly ignored, in its application. The first concerns selecting the correct comparison energy price; the second involves maintaining a consistent economic perspective throughout the analysis. (This is discussed in Chapter 6.)

## 4.3 Selecting the Comparison Energy Price

The rule for making a decision based upon the CCE is simple: "Select only those measures having a CCE less than the price of the energy they displace." But what is the price of energy? Since the conservation measure will last several years and energy prices will certainly change, the current energy price cannot always be used as a comparison price. This section provides information on the proper selection of the comparison (or "cut-off") energy price.

What is the meaning of using the current energy price as the comparison price? Comparing the CCE to today's energy price is equivalent to assuming that real (inflation-removed) energy prices will not change over a measure's lifetime; that is, we assume a "zero per cent real (inflation-adjusted) fuel escalation rate." If we expect energy prices to rise faster than inflation, then the current price is an unrealistically low cut-off price.

The correct comparison price is the levelized energy price for the period in which the conservation measure will operate (or is being amortized).[2] Figure 4-1 shows the comparison price for three fuel escalation rates. (The comparison price is simply the levelized price assuming exponential growth.) The comparison price is given in units of $P_{comp}/P_o$, where $P_o$ is the current energy price and $P_{comp}$ is the comparison energy price. For example, if the real fuel escalation rate is 3% and the conservation measure's amortization time is 10 years, then $P_{comp}/P_o = 1.17$. The correct comparison price for conservation measures is then 1.17 times the current energy price. Table 4-1 shows the comparison prices for a wider range of discount rates. Clearly the adjustment is most significant for long-lived conservation measures and high escalation rates. For example, a 20-year lifetime and a 5% real fuel escalation rate leads to a $P_{comp}/P_o = 1.72$.

It is simpler to calculate the CCE using a real (or inflation-removed) discount rate. Likewise, working with inflation-removed prices simplifies estimation of the investment when future maintenance costs must be included. To remain consistent, we must then compare it to the increases in real energy price over the lifetime of the measure. Again, for rough estimates, the assumption of constant real energy prices facilitates selection of a comparison price.

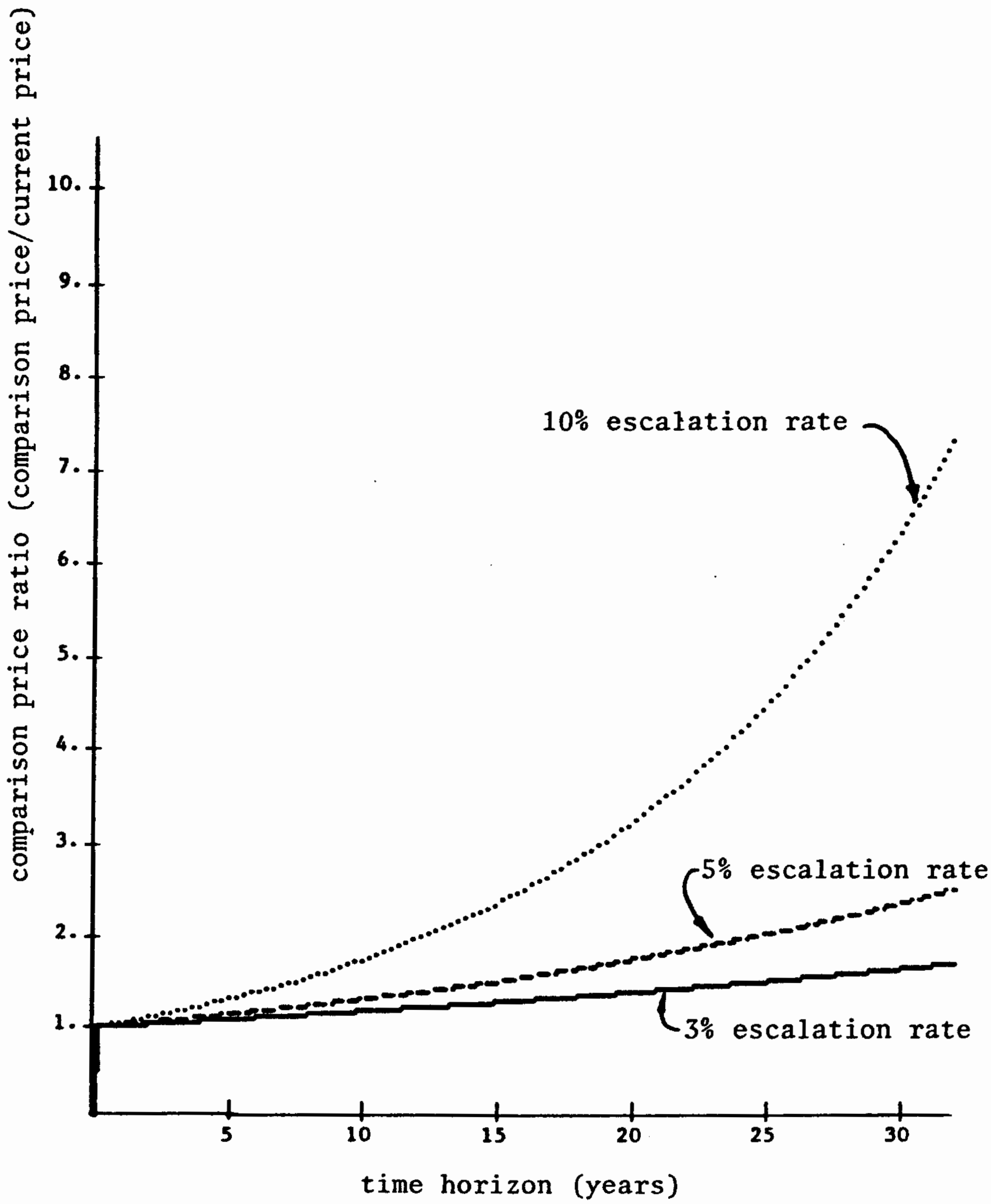


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Figure 4-1. The adjustment of the current energy price to permit comparison with the cost of conserved energy. If energy prices are expected to rise, then the weighted average of future energy prices should be used in place of the current price. Select the lifetime (or time horizon) on the x-axis. Read the comparison energy price ratio on the y-axis for appropriate rate of energy price escalation. Multiply the current energy price by the ratio to obtain the comparison energy price.

Comparison Energy Price (comparison price/initial price)

| lifetime (years) | fuel escalation rate 2% | 4% | 6% | 8% | 10% | 12% | 14% | 16% |
|---|---|---|---|---|---|---|---|---|
| 2 | 1.02 | 1.04 | 1.06 | 1.08 | 1.11 | 1.13 | 1.15 | 1.18 |
| 4 | 1.04 | 1.08 | 1.13 | 1.18 | 1.23 | 1.28 | 1.34 | 1.40 |
| 6 | 1.06 | 1.13 | 1.20 | 1.28 | 1.37 | 1.46 | 1.57 | 1.68 |
| 8 | 1.08 | 1.18 | 1.28 | 1.40 | 1.53 | 1.68 | 1.84 | 2.03 |
| 10 | 1.11 | 1.23 | 1.37 | 1.53 | 1.72 | 1.93 | 2.18 | 2.47 |
| 12 | 1.13 | 1.28 | 1.46 | 1.68 | 1.93 | 2.24 | 2.60 | 3.03 |
| 14 | 1.15 | 1.34 | 1.57 | 1.84 | 2.18 | 2.60 | 3.11 | 3.75 |
| 16 | 1.18 | 1.40 | 1.68 | 2.03 | 2.47 | 3.03 | 3.75 | 4.66 |
| 18 | 1.20 | 1.46 | 1.80 | 2.24 | 2.81 | 3.55 | 4.54 | 5.84 |
| 20 | 1.23 | 1.53 | 1.93 | 2.47 | 3.19 | 4.18 | 5.52 | 7.35 |
| 22 | 1.26 | 1.60 | 2.08 | 2.73 | 3.65 | 4.93 | 6.74 | 9.31 |
| 24 | 1.28 | 1.68 | 2.24 | 3.03 | 4.18 | 5.84 | 8.27 | 11.86 |
| 26 | 1.31 | 1.76 | 2.41 | 3.37 | 4.79 | 6.94 | 10.19 | 15.16 |
| 28 | 1.34 | 1.84 | 2.60 | 3.75 | 5.52 | 8.27 | 12.60 | 19.47 |
| 30 | 1.37 | 1.93 | 2.81 | 4.18 | 6.36 | 9.89 | 15.64 | 25.11 |

Table 4-1. Comparison energy prices for several energy price escalation rates. The elements of the table are expressed as ratios, comparison price/current price. To obtain the comparison price, multiply the appropriate ratio (as determined by escalation rate and lifetime) by the current energy price.

## 4.4 References and Notes

1. See, for example, E. J. Mishan, Cost Benefit Analysis (New York: Praeger Publishers, 1971).

2. The levelizing formula is:

$$\frac{P_{comp}}{P_{initial}} = \frac{e^{rt} - 1}{rt}$$

where,

$P_{comp}$ = comparison price

$P_{initial}$ = initial price

r = escalation rate

t = amortization time

# Chapter 5: SENSITIVITY AND ERRORS

# 5. SENSITIVITY AND ERRORS

This chapter examines the consequences new that information, different assumptions, or errors in the energy-conservation data can have on the supply curves of conserved energy. The first section is a sensitivity analysis for the cost of conserved energy; it applies to a single conservation measure. Following sections trace the consequences of these errors on a sequence of measures as displayed on a conservation supply curve--that is, the inter-measure effects of errors.

Much of the following discussion would apply to any analysis of conservation potentials. However, the supply curve approach allows a more generalized treatment of the problems of maintaining a consistent framework for estimating the conservation potential.

## 5.1 Sensitivity of the Cost of Conserved Energy

The cost of conserved energy (CCE) is calculated using the following formula:

$$CCE = \frac{I}{E} \cdot \frac{d}{1 - (1+d)^{-n}}$$

where, I = cost of measure (investment)
E = energy savings per year
d = discount rate
n= amortization time.

The equation is plotted in Figure 5-1 for four discount rates.[1] Note that, because the ratio of I/E has been assumed to equal one, this is also a plot of the capital recovery rate.

Four variables affect the CCE: the measure's cost, the annual energy savings, the amortization time, and the discount rate. New information, or another economic perspective, may change the original values for a measure. To avoid unnecessary computation, it is useful to know which variables affect the CCE most strongly.

The CCE's sensitivity can be described as similar to the economic measure of elasticity. The elasticity is that percentage change in the dependent variable resulting from a 1% change in the independent variable. The elasticities for the CCE are given in Table 5-1. The elasticities with respect to cost, I, and energy savings, E, are 1 and -1 respectively; that is, a 1% increase in cost leads to a 1% increase in the CCE and a 1% increase in energy savings leads to a 1% <u>de</u>crease in the CCE. The remaining elasticities, those with respect to the discount rate, d, and amortization time, n, are plotted in Figure 5-2.

An elasticity having a value less than one indicates that a 1% change in the independent variable causes less than a 1% change in the CCE. The lower the elasticity, the less sensitive the CCE.

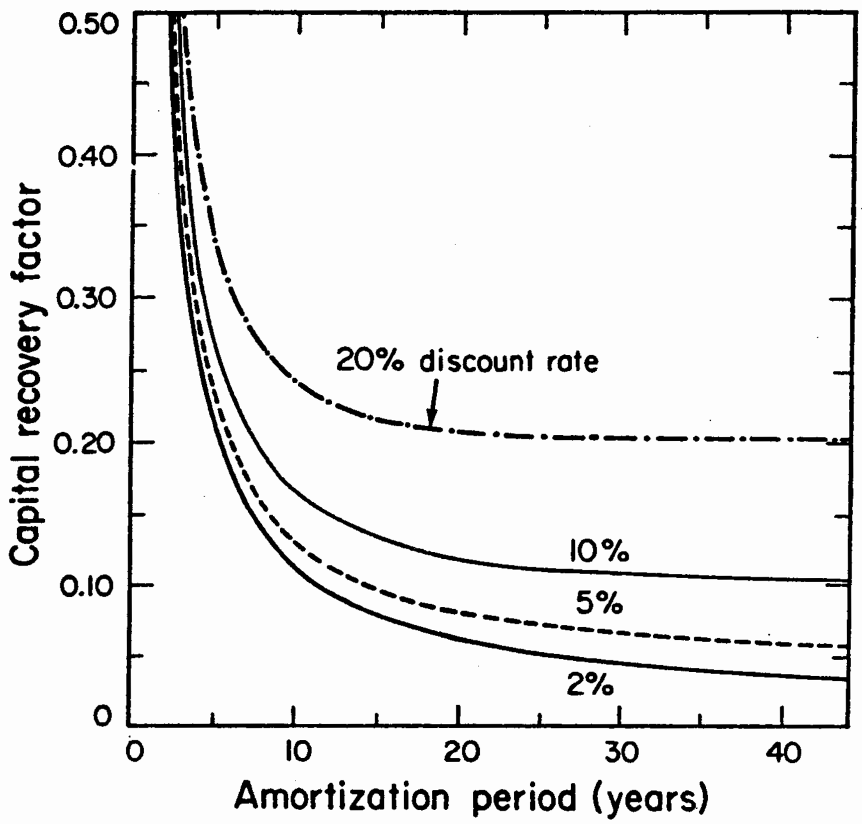


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Figure 5-1. The relationship between amortization period and capital recovery factor for four discount rates. The capital recovery factor is also the cost of conserved energy when the ratio of cost over energy savings (I/E) equals one.

Elasticity with respect to investment:

$$\eta_I = \frac{\partial CCE}{\partial I} \frac{I}{CCE} = +1$$

Elasticity with respect to energy savings:

$$\eta_E = \frac{\partial CCE}{\partial E} \frac{E}{CCE} = -1$$

Elasticity with respect to amortization time:

$$\eta_n = \frac{\partial CCE}{\partial n} \frac{n}{CCE} = \frac{n \; ln \; (1+d)}{1 - (1+d)^n}$$

Elasticity with respect to discount rate:

$$\eta_d = \frac{\partial CCE}{\partial d} \frac{d}{CCE} = 1 + \frac{n \; d}{(1+d)^{n+1} - (1+d)}$$

where,

$$CCE = \frac{I}{E} \frac{d}{1 - (1+d)^{-n}}$$

**Table 5-1. Elasticities of the cost of conserved energy with respect to the measure's cost, energy savings, amortization time, and discount rate.**

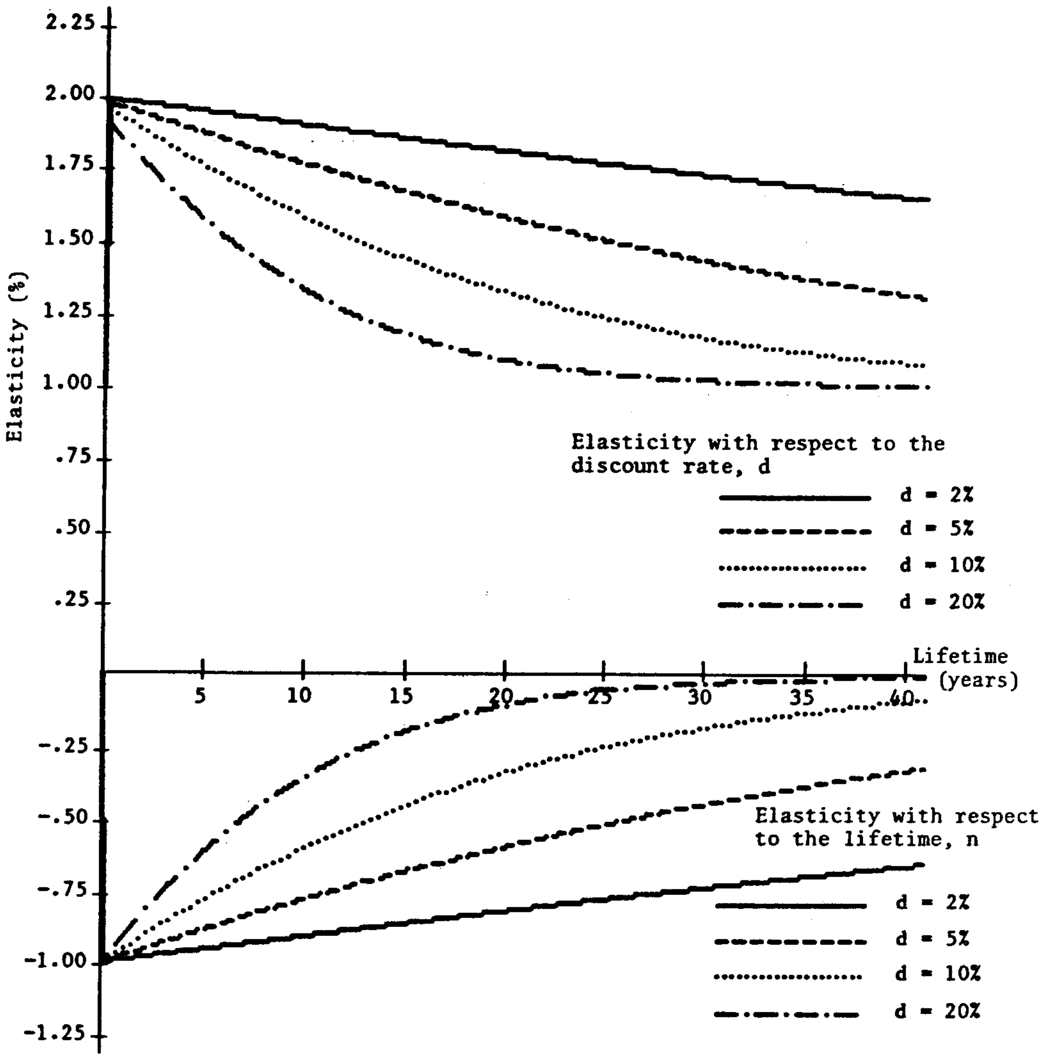


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Figure 5-2. The elasticity of the cost of conserved energy with respect to the discount rate (above) and the lifetime (below).

Elasticities near zero are best from the standpoint of low sensitivity, although an insensitive investment statistic is undesirable, too. Figure 5-2 and Table 5-1 show that all of the elasticities range from -1 to +2 over typical values. The elasticities are well behaved; that is, they do not have discontinuities or regions where they are undefined.

Figure 5-2 shows that the CCE is most sensitive to changes in the discount rate, d. Not only are these elasticities the largest; so too are the expected absolute changes in the rate. Costs of conserved energy are often calculated in real (inflation-removed) terms. Discount rates from 3 to 7% are common. A 1% change in discount rate, for example from 5% to 5.05%, is typically considered small. Shifting from a 5% to 7% rate is a reasonable sensitivity check; it corresponds to a 40% increase in d, and a roughly (1.28 x 40) 52% increase in the CCE. Together these factors make changes in the discount rate especially significant.

The elasticities indicate that there are no surprises, or "time bombs," hidden within the cost-of-conserved-energy calculations. The CCE is moderately sensitive to changes in the inputs -- most elasticities are near one -- but the typical CCEs do not border on regions of instability. At low discount rates (1 - 5%), the elasticities approach 2. Care should be taken in this range since these are the rates typically chosen for real or constant-dollar discount rates. Moving from a discount rate of 2% to 3% can raise the CCE 80%.

## 5.2 Uncertainty and Errors Between Measures

A supply curve of conserved energy is an ordered display of conservation measures based on their respective costs of conserved energy. New information or errors like those discussed above will change the costs of conserved energy and may necessitate reordering the measures. This section examines how changes in the CCE affect the energy savings attributed to measures and their <u>order</u> on the supply curve. Again, much of this discussion applies to the general understanding of the energy and economic relationships between conservation measures. However, the consistent framework of conservation supply curves permits more concise statements of the relations.

The examples will refer to a micro supply curve of conserved energy (that is, a single home), although the observations also apply to an aggregate supply curve. Most of the concepts are simpler to describe when the stock is limited to one item; however, unique problems associated with a heterogeneous stock are presented later.

## 5.3 Energy Service Curves

Energy service curves depict the relationship between the energy use of an appliance or process and the service provided. Further, they show the consequences of different conservation measures. Figure 5-3 is a schematic energy service curve. An energy service curve shows how the appliance converts "raw" energy into a more useful form. Once the

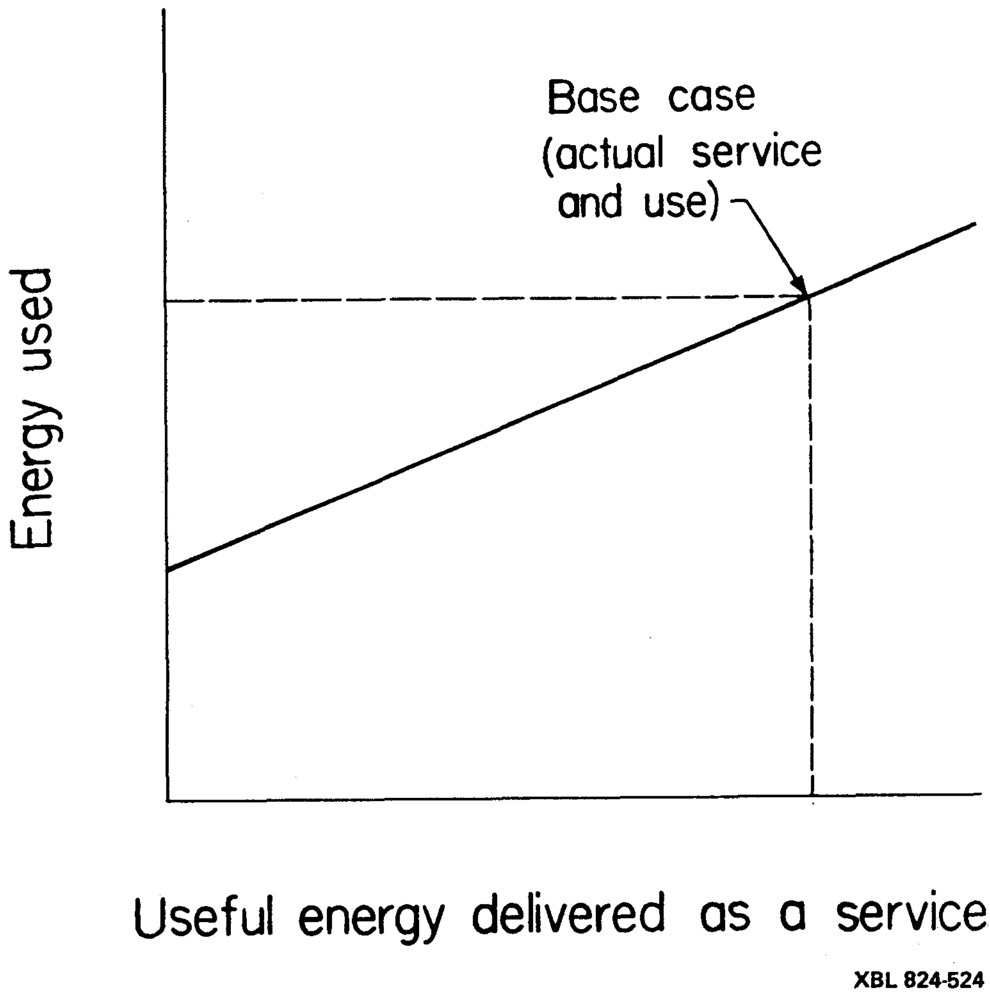


Figure 5-3. An energy service curve. The horizontal axis is the energy delivered in a usable form, that is, the service. For a water-heating service curve, the axis would represent the amount of energy embodied in the hot water delivered. The axis may also have dimensions associated with the service rather than energy. An energy service curve for lighting would more likely have dimensions of lumens (or lumen-hours) to indicate the amount of useful illumination delivered. The vertical axis represents the energy consumed to provide the service, i.e. what the consumer pays for. In an energy-service curve for a gas water heater, for example, this is the natural gas consumed.

service curve for a particular unit has been developed, we can locate a particular situation on the curve by knowing either the amount of service provided or energy used.

Energy service curves often have a positive y-intercept, implying that the appliance consumes energy even when providing no useful service. This is commonly called a "standby loss" and occurs when energy is stored (such as in water heaters), a temperature differential is maintained (such as in refrigerators), or a pilot light is burning (as in furnaces). The service (mechanical drive, space conditioning, etc.) does not require these features; rather, the curves reflect the the technology employed to provide the service. For example, an instantaneous (or "flash") water heater will have no standby losses because it heats water only when there is an immediate demand. Similarly, a car powered by an electric motor (rather than an internal combustion engine) has no idling losses.

The slope of an energy service curve corresponds to the reciprocal of the appliance's efficiency. Lower efficiencies translate into steeper curves, i.e., more service for less energy.

Energy service curves do not ideally describe appliance behavior. They do not indicate whether all the useful energy delivered is actually needed. The curves give no clue that a furnace produces the same amount of useful heat for a large, tight home as a small, leaky home. Second, they do not distinguish between instantaneous and time-integrated behavior. This becomes important when a device operates frequently at part-load or "cycles." The effects of part-load efficiency do not appear when annual or monthly consumption is plotted. Still, the curves illustrate the consequences of some important conservation measures.

There are three kinds of conservation measures:

1. a reduction in demand
2. an improvement in efficiency
3. a reduction in standby loss.

Conservation measures not directly related to the device can reduce demand while providing the same level of service. A low-flow showerhead requires less hot water from the water heater; a more streamlined truck needs less engine output to maintain the same speed. A reduction in demand corresponds to a movement down the original service curve, as shown in Figure 5-4. In the first case, the energy savings will be independent of position in the sequence while, in the second case, the energy savings must be recalculated each time the measure's position in the sequence is changed.

An efficiency improvement results in a more shallow slope in the service curve; that is, more service is provided by less energy. Note that the curve may be rotated either from the y-intercept or the extension of the line to the x-intercept, depending on the type of standby loss. A furnace system that is more efficient, but still relies on a pilot light, would correspond to a rotation about the y-intercept. In contrast, an improvement in water-heater efficiency corresponds to a rotation about the x-intercept (because the standby loss is made up more

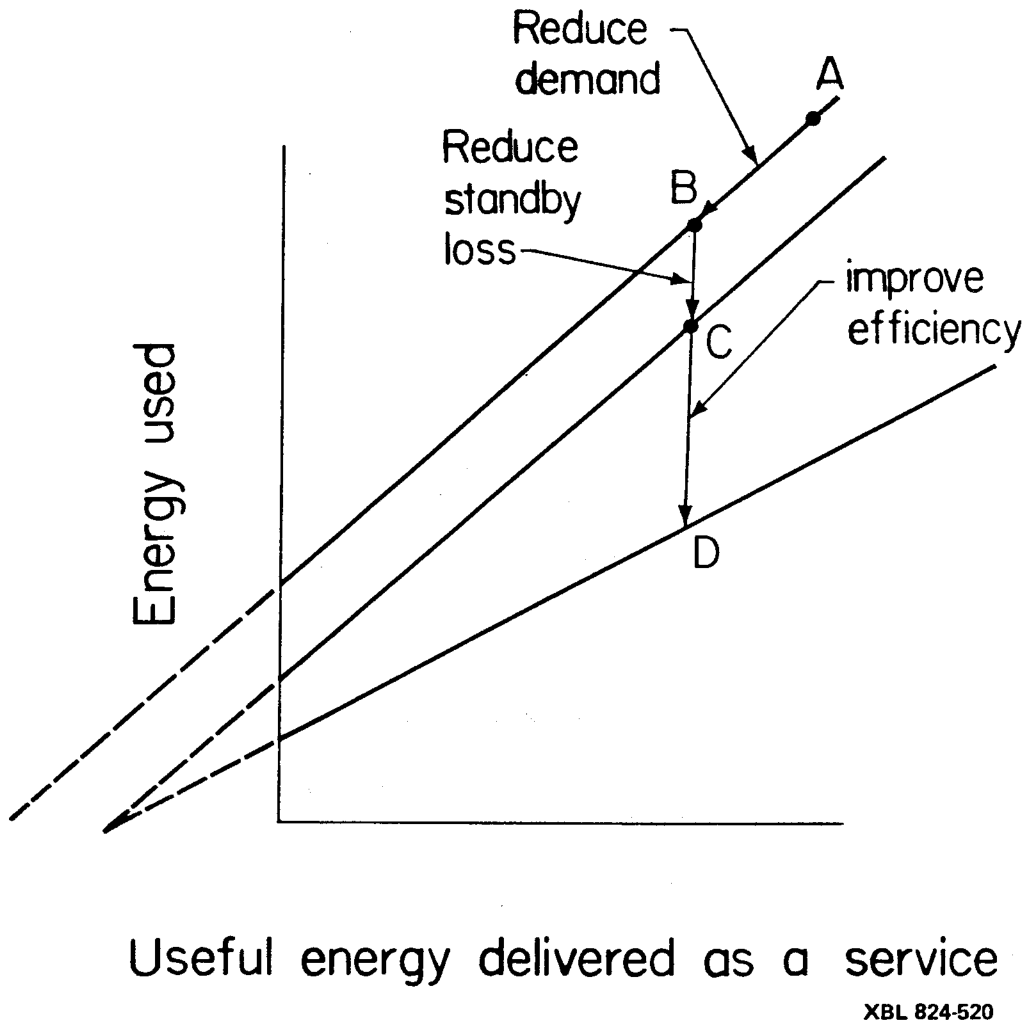


Figure 5-4. The three types of conservation measures shown on an energy-service curve.

efficiently, too).

The standby loss is typically independent of original consumption. Therefore a reduction in standby loss will be the same over the entire range of output. A reduction in standby loss corresponds to a downward shift of the original service curve; this is also shown in Figure 5-4.

Now consider a sequence of conservation measures made up of demand reductions, improvements in efficiency, and reduced standby loss. An example of a sequence for space heating is shown in Figure 5-5, along with an explanatory table (Table 5-2). Table 5-2 lists the measures in order of increasing CCE and therefore defines a supply curve of conserved energy.

Clearly the total energy savings attributed to the package of measures does not change. On the other hand, the energy savings attributed to individual measures will change in response to the order. Table 5-3 shows the energy savings for each measure assuming it was implemented first. The earlier in a sequence a measure is performed the more energy it will save; in general it will save the most when done first (which is the same as being done independently).

This order-dependence of energy savings has two implications. First, energy savings are not simply additive. The sum of individual measures' savings--as if each were implemented first--will be greater than if they were treated as a package. (More precisely, they are anti-synergistic.) Table 5-3 shows that treating the measures independently would have overestimated the total energy savings by 24 GJ. This is a result of "double-counting" energy savings.

Second, the cost of conserved energy for a measure will depend upon the measure's position in the sequence. The energy savings enter into the CCE calculation, so the CCE must be recalculated each time its position is shifted. This iterative process must be performed until the measures are ordered in terms of increasing CCE based on their energy savings at that position. The computer program used to calculate the energy savings shown in Tables 5-2 through 5-12 has this iterative capability. The code is presented in the Appendix.

This interdependence of energy savings and the cost of conserved energy complicates the construction of supply curves of conserved energy (or any other energy-accounting scheme for conservation potentials). To avoid the confusion caused by a great range in possible energy savings, we always assume that all cheaper (i.e, lower-CCE) measures have been implemented before calculating the energy savings. This is the foundation for what we call a "consistent accounting framework." The assumption also permits direct addition of energy savings without fear of double-counting. Poor data, but not logical inconsistencies, will lead to inaccurate estimates of the conservation potential.

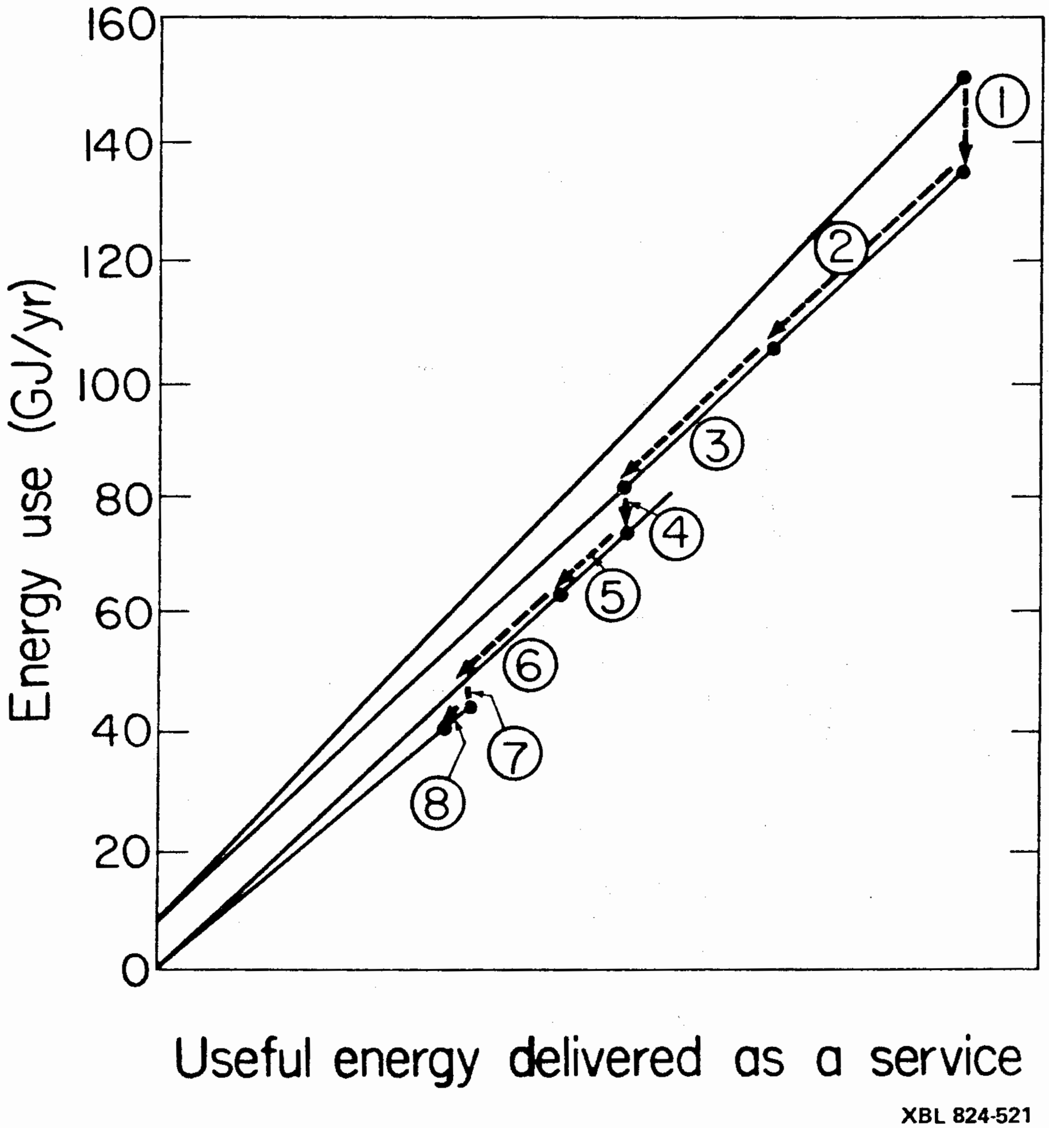


Figure 5-5. An energy-service curve for a series of space-heating conservation measures. The numbers correspond to the measures listed in Table 5-2.

initial conditions and assumptions:

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 300.0 | 25.0 | 1.6 | 136.8 | 13.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.8 | 105.1 | 31.7 |
| 3. add attic insulation | 700.0 | 30.0 | 1.9 | 81.0 | 24.2 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 74.0 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 63.6 | 10.3 |
| 6. install storm windows | 800.0 | 20.0 | 4.5 | 49.3 | 14.3 |
| 7. tuneup furnace | 65.0 | 3.0 | 6.0 | 45.4 | 3.9 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 7.1 | 41.7 | 3.6 |
| | | | | Total | 108.6 |

Final conditions after retrofit:

| | | |
|---|---|---|
| energy use | = | 41.7 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.72 |
| discount rate | = | 5.0 % per year |

Table 5-2. A sequence of space-heating conservation measures for a hypothetical house. They are listed in order of increasing cost of conserved energy. Note that the total savings after the final measure is 108.6 GJ/year. This table serves as the base case for subsequent examples.

**initial conditions and assumptions:**

| | |
|---|---|
| energy use | = 150.3 (GJ/year) |
| thermostat setting | = 22.0 (deg. C) |
| attic conduction loss | = 20.0 (GJ/year) |
| wall conduction loss | = 35.0 (GJ/year) |
| infiltration loss | = 18.0 (GJ/year) |
| window loss | = 13.0 (GJ/year) |
| pilot loss | = 7.0 (GJ/year) |
| furnace syst.effic. | = 0.60 |
| discount rate | = 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. add attic insulation | 700.0 | 30.0 | 1.7 | 123.6 | 26.7 |
| 1. add wall insulation | 900.0 | 30.0 | 1.7 | 115.3 | 35.0 |
| 1. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 143.3 | 7.0 |
| 1. install storm windows | 800.0 | 20.0 | 4.1 | 134.5 | 15.8 |
| 1. weatherstrip | 300.0 | 10.0 | 3.4 | 138.9 | 11.4 |
| 1. tuneup furnace | 65.0 | 3.0 | 2.1 | 138.8 | 11.5 |
| 1. thermostat set back, 22->20 | 200.0 | 10.0 | 2.3 | 138.8 | 11.5 |
| 1. insulate ducts | 300.0 | 25.0 | 1.6 | 136.8 | 13.4 |
| | | | | Total | 132.3 |

Table 5-3. Energy savings for the base case house assuming each measure was implemented first. Note that the total energy savings would be 132.3 GJ/year, more than in Table 5-2, due to double-counting of energy savings.

## 5.4 Error Propagation in Supply Curves

Small errors in calculating the cost of conserved energy only affect the vertical coordinate of the supply curves. However, larger adjustments in the CCE may cause a reshuffling of the conservation measures, depending on the closeness of the CCEs. If the measures are interdependent, this may change the energy savings and force a recalculation of CCEs. Sequences of interdependent conservation measures, which are very common within a single end use, are our principal concern.

It is inevitable that, after a supply curve is developed, we will return to it with either new information or changes in assumptions. We therefore need to know what kinds of conclusions can be made without laborious recalculations. The following are observations regarding the consequences of adjustments in assumptions -- called "errors" for simplicity -- on supply curves of conserved energy. We will continue with the example of space heating presented in Table 5-2, which serves as the "base case" for subsequent examples. Tables for conservation supply curves are presented, rather than the curves themselves, to emphasize the numerical changes.

5.4a. An Error in a Measure's Cost. Small changes in a measure's cost are usually innocuous. A higher cost will raise the measure's CCE and leave the remainder of the curve (i.e., subsequent measures having higher CCEs) intact. Table 5-4 shows an example for an increase in the cost of duct insulation from \$300 to \$315. The CCE increased from \$1.6/GJ to \$1.7/GJ, which left it first in the sequence.

Larger changes in cost will not only change that measure's CCE, but may also affect neighboring measures' energy savings and CCEs. If the measures are independent, then a simple reordering results, leaving other CCEs and energy savings intact. A reordering in an interdependent sequence often forces recalculation of other measures' CCEs.

When the cost of duct insulation rose from \$300 to \$350, the CCE rose to \$1.85/GJ. It then exceeded that of wall insulation, and the two measures switched positions. But duct insulation saved less energy when implemented after wall insulation. This increased its CCE (due to the smaller energy savings) so that it exceeded the CCE for attic insulation, so duct insulation dropped to position number three. Duct insulation also saved less energy when implemented after attic insulation, thus further increasing its CCE. That CCE exceeded the CCE for the intermittent ignition device, so duct insulation dropped to number four. The CCE did not change here because the savings from duct insulation are independent of energy savings from the intermittent ignition device. The final order is shown in Table 5-5.[2]

Note that raising the measure's cost 17% reduced the energy savings attributed to duct insulation 40% (from 13.4 GJ in the base case to 7.7 GJ). In addition, the CCE doubled (from \$1.6/GJ to \$3.2/GJ). Reordering, rather than increase in cost, was responsible for the greatest part of this change.

5.4b An Error in a Measure's Lifetime. Changes in a measure's lifetime cause perturbations in a sequence similar to changes in a measure's cost. Small reductions in lifetime raise the CCE but leave neighboring

initial conditions and assumptions:

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 315.0 | 25.0 | 1.7 | 136.8 | 13.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.8 | 105.1 | 31.7 |
| 3. add attic insulation | 700.0 | 30.0 | 1.9 | 81.0 | 24.2 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 74.0 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 63.6 | 10.3 |
| 6. install storm windows | 800.0 | 20.0 | 4.5 | 49.3 | 14.3 |
| 7. tuneup furnace | 65.0 | 3.0 | 6.0 | 45.4 | 3.9 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 7.1 | 41.7 | 3.6 |

Final conditions after retrofit:

| | | |
|---|---|---|
| energy use | = | 41.7 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.72 |
| discount rate | = | 5.0 % per year |

Table 5-4. The optimal sequence of conservation measures for a small change in the cost of a measure. Here, the cost of duct insulation was raised from $300 in the base case to $315. The order of the measures did not change, although the first measure's CCE increased to $1.7/GJ.

initial conditions and assumptions:

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. add wall insulation | 900.0 | 30.0 | 1.7 | 115.3 | 35.0 |
| 2. add attic insulation | 700.0 | 30.0 | 1.7 | 88.6 | 26.7 |
| 3. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 81.6 | 7.0 |
| 4. insulate ducts | 350.0 | 25.0 | 3.2 | 74.0 | 7.7 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 63.6 | 10.3 |
| 6. install storm windows | 800.0 | 20.0 | 4.5 | 49.3 | 14.3 |
| 7. tuneup furnace | 65.0 | 3.0 | 6.0 | 45.4 | 3.9 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 7.1 | 41.7 | 3.6 |

Final conditions after retrofit:

| | | |
|---|---|---|
| energy use | = | 41.7 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.72 |
| discount rate | = | 5.0 % per year |

Table 5-5. The optimal sequence of conservation measures for a larger change in the cost of a measure. Here, the cost of duct insulation was raised from $300 in the base case to $350. As a result, the order of the measures changed; duct insulation shifted from first in the base case to fourth here. Note that the energy savings attributed to attic and wall insulation increased as a result of the reordering.

measures unaffected. Table 5-6 illustrates a decrease in the lifetime of duct insulation from 25 (in the base case) to 24 years.

Larger changes in lifetime may cause reordering and necessitate recalculation of the neighboring measures' CCEs. Such a case is presented in Table 5-7, where the lifetime for duct insulation is assumed to be 22 years. Duct insulation dropped to fourth in the sequence.

5.4c An Error in a Measure's Discount Rate.

A unique discount rate could in principle be associated with each conservation measure. Errors in a single measure's discount rate will propagate in a manner similar to the way errors in lifetime and cost propagate. The elasticity curve (Figure 5-2) indicates that the CCE is sensitive to changes in discount rate, so reordering is likely.

Changing the discount rate for all measures is much more common. Changes in the discount rate affect the CCEs of longer-lived measures more than they affect those with shorter lifetimes. Reducing the discount rate lowers the CCE of all measures, but disproportionately more for measures having long lifetimes. Figure 5-6 shows how increasing the discount rate increases the CCE. The SERI study referred to here used a 3% discount rate in calculating the cost of conserved energy.[3] A 20% rate caused substantial rearrangement of the measures due to differences in lifetime; some measures shifted as much as 13 positions. (These curves were made using a rather primitive program which could not recalculate the energy savings after reordering. Each measure's energy savings are thus "frozen" so that the shifts displayed understate the true effect. In contrast, the program used for the micro examples recalculates the energy savings as a sequence is rearranged.)

Tables 5-8 and 5-9 show the same sequence of conservation measures run first with a 2% and then with a 20% discount rate. A substantial rearrangement occurred. The furnace-tuneup measure appeared last in the sequence at 2% and first at 20%. Note also that the energy savings attributed to the tuneup increased threefold. At a high discount rate, the short-lived measures drifted towards the top of the sequence. Weatherstripping and storm windows, which are uneconomical under any circumstance, drifted somewhat downwards because another efficiency measure jumped ahead of them. This reduced the savings attributed to them, and increased their CCEs.

5.4d An Error in the Initial Energy Use. Because many conservation measures save a certain percentage of the initial energy use rather than a fixed amount, a revision of the initial energy use will affect the energy savings of some measures. An adjustment of energy savings will affect CCEs and, sometimes, the order of measures (forcing yet another iteration). An overestimate of the initial energy use will lead to overestimates of energy savings and underestimates of the CCEs for subsequent measures. The corrected curve will lie below the original curve and be compressed horizontally.

initial conditions and assumptions:

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 300.0 | 24.0 | 1.6 | 136.8 | 13.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.8 | 105.1 | 31.7 |
| 3. add attic insulation | 700.0 | 30.0 | 1.9 | 81.0 | 24.2 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 74.0 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 63.6 | 10.3 |
| 6. install storm windows | 800.0 | 20.0 | 4.5 | 49.3 | 14.3 |
| 7. tuneup furnace | 65.0 | 3.0 | 6.0 | 45.4 | 3.9 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 7.1 | 41.7 | 3.6 |

Final conditions after retrofit:

| | | |
|---|---|---|
| energy use | = | 41.7 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.72 |
| discount rate | = | 5.0 % per year |

Table 5-6. The optimal sequence of conservation measures for a small change in the lifetime of a measure. Here, the lifetime of duct insulation was reduced from 25 years in the base case to 24 years. This raised the CCE for duct insulation but did not affect the order of the measures.

**initial conditions and assumptions:**

| | |
|---|---|
| energy use | = 150.3 (GJ/year) |
| thermostat setting | = 22.0 (deg. C) |
| attic conduction loss | = 20.0 (GJ/year) |
| wall conduction loss | = 35.0 (GJ/year) |
| infiltration loss | = 18.0 (GJ/year) |
| window loss | = 13.0 (GJ/year) |
| pilot loss | = 7.0 (GJ/year) |
| furnace syst.effic. | = 0.60 |
| discount rate | = 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. add wall insulation | 900.0 | 30.0 | 1.7 | 115.3 | 35.0 |
| 2. add attic insulation | 700.0 | 30.0 | 1.7 | 88.6 | 26.7 |
| 3. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 81.6 | 7.0 |
| 4. insulate ducts | 300.0 | 22.0 | 3.0 | 74.0 | 7.7 |
| 5. weatherstrip | 300.0 | 10.0 | 3.8 | 63.6 | 10.3 |
| 6. install storm windows | 800.0 | 20.0 | 4.5 | 49.3 | 14.3 |
| 7. tuneup furnace | 65.0 | 3.0 | 6.0 | 45.4 | 3.9 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 7.1 | 41.7 | 3.6 |

**Final conditions after retrofit:**

| | |
|---|---|
| energy use | = 41.7 (GJ/year) |
| thermostat setting | = 20.0 (deg. C) |
| attic conduction loss | = 3.7 (GJ/year) |
| wall conduction loss | = 12.9 (GJ/year) |
| infiltration loss | = 10.3 (GJ/year) |
| window loss | = 3.2 (GJ/year) |
| pilot loss | = 0.0 (GJ/year) |
| furnace syst.effic. | = 0.72 |
| discount rate | = 5.0 % per year |

Table 5-7. The optimal sequence of conservation measures for a larger change in the lifetime of a measure. Here, the lifetime of duct insulation was reduced from 25 years in the base case to 22 years. As a result, the order of the measures changed; duct insulation shifted from first in the base case to fourth here. Note that the energy savings attributed to attic and wall insulation increased as a result of the reordering.

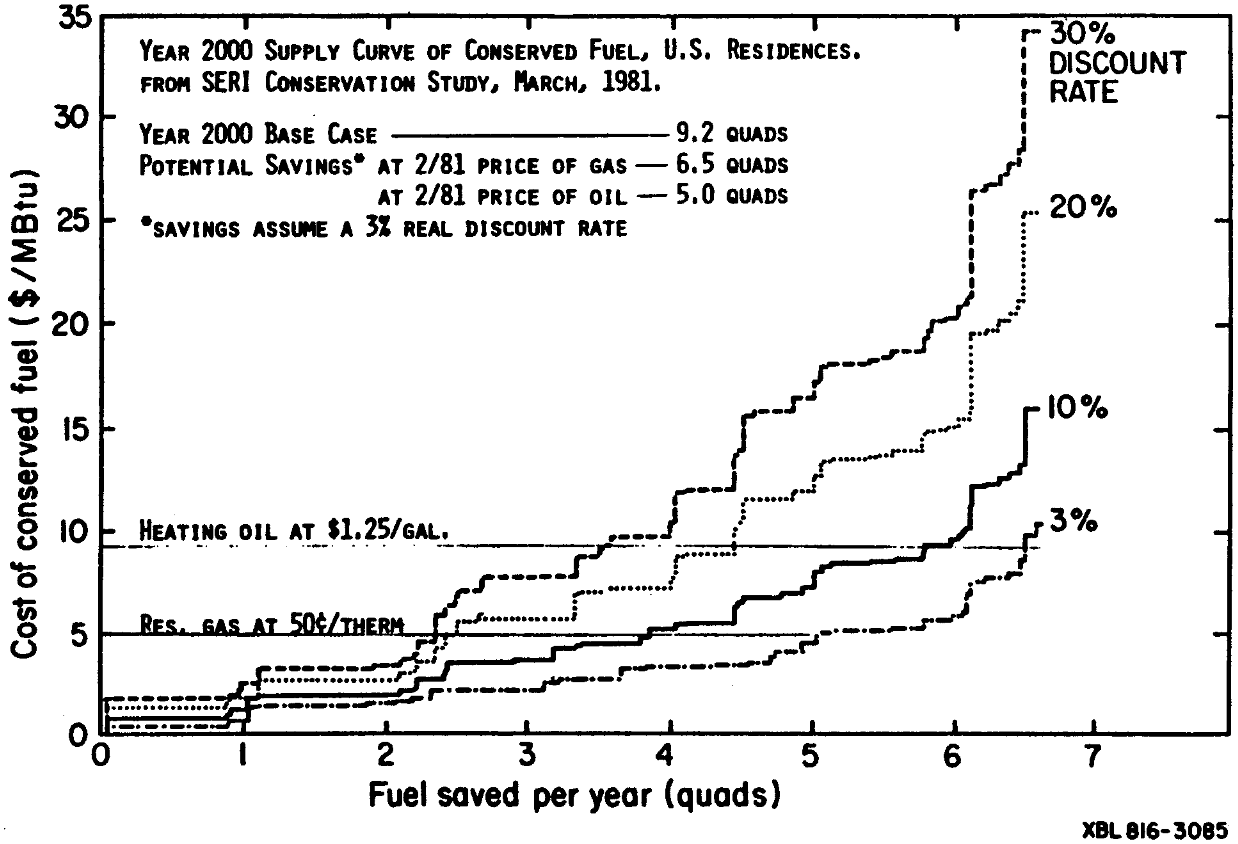


Figure 5-6. A supply curve of conserved fuel with different discount rates. Raising the discount rate increases the cost of conserved energy. It also reshuffled the sequence. This is visible at 3.3 quads, where the reordering led to a sharp jump appearing earlier in the 3% and 10% curves than in the 20% curve.

**initial conditions and assumptions:**

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 2.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 300.0 | 25.0 | 1.1 | 136.8 | 13.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.3 | 105.1 | 31.7 |
| 3. add attic insulation | 700.0 | 30.0 | 1.3 | 81.0 | 24.2 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.4 | 74.0 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.2 | 63.6 | 10.3 |
| 6. install storm windows | 800.0 | 20.0 | 3.4 | 49.3 | 14.3 |
| 7. thermostat set back, 22->20 | 200.0 | 10.0 | 5.6 | 45.4 | 3.9 |
| 8. tuneup furnace | 65.0 | 3.0 | 6.2 | 41.7 | 3.6 |

**Final conditions after retrofit:**

| | | |
|---|---|---|
| energy use | = | 41.7 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.72 |
| discount rate | = | 2.0 % per year |

Table 5-8. The optimal sequence of conservation measures for a 2% discount rate. The order of the first six measures is identical to the base case (run at 5%); however, the last two measures switched places. The CCE for the thermostat-setback measure, with its longer lifetime, fell more rapidly than for the furnace-tuneup measure.

**initial conditions and assumptions:**

```
energy use             = 150.3 (GJ/year)
thermostat setting     =  22.0 (deg. C)
attic conduction loss  =  20.0 (GJ/year)
wall conduction loss   =  35.0 (GJ/year)
infiltration loss      =  18.0 (GJ/year)
window loss            =  13.0 (GJ/year)
pilot loss             =   7.0 (GJ/year)
furnace syst.effic.    =   0.60
discount rate          =  20.0 % per year
```

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. tuneup furnace | 65.0 | 3.0 | 2.7 | 138.8 | 11.5 |
| 2. thermostat set back, 22->20 | 200.0 | 10.0 | 4.5 | 128.3 | 10.5 |
| 3. intermittent ignit. device | 150.0 | 10.0 | 5.1 | 121.3 | 7.0 |
| 4. insulate ducts | 300.0 | 25.0 | 5.3 | 109.9 | 11.4 |
| 5. add wall insulation | 900.0 | 30.0 | 6.7 | 83.1 | 26.8 |
| 6. add attic insulation | 700.0 | 30.0 | 6.9 | 62.6 | 20.4 |
| 7. weatherstrip | 300.0 | 10.0 | 8.2 | 53.9 | 8.7 |
| 8. install storm windows | 800.0 | 20.0 | 13.5 | 41.7 | 12.1 |

**Final conditions after retrofit:**

```
energy use             =  41.7 (GJ/year)
thermostat setting     =  20.0 (deg. C)
attic conduction loss  =   3.7 (GJ/year)
wall conduction loss   =  12.9 (GJ/year)
infiltration loss      =  10.3 (GJ/year)
window loss            =   3.2 (GJ/year)
pilot loss             =   0.0 (GJ/year)
furnace syst.effic.    =   0.72
discount rate          =  20.0 % per year
```

Table 5-9. The optimal sequence of conservation measures for a 20% discount rate. The order of the measures is now completely different than the base case which used 5%. Measures with shorter lifetimes moved up in the sequence because their CCEs are less sensitive to changes in discount rate. Note that the energy savings attributed to each measure also differs from the base case.

Table 5-10 shows the consequences of overestimating the initial attic conduction losses (raised from 20 GJ/yr in the base case to 40 GJ/yr). The savings from attic insulation rose commensurately, thus lowering that measure's CCE below duct and wall insulation. Greater overall conduction losses (even after attic insulation) made the furnace tuneup measure more attractive; hence it moved. Overestimating the initial energy use led to significant reordering of measures not even directly related to the original error. This example underscores the importance of carefully establishing initial energy consumption.

5.4e An Error in Energy Savings. Errors may also occur in the algorithm used to estimate the savings for a measure, as opposed to in the initial conditions (above). An overestimate of a measure's energy savings leaves less energy for subsequent measures to save. The corrected supply curve would branch at the measure where the error occurred (its step would be narrower). Subsequent measures would lie (for the most part) on a curve above the original, incorrect curve.

Table 5-11 illustrates the effect of an algorithm error. In the base case, the duct insulation measure was assumed to yield a 96% efficient duct system. Table 5-11 shows the result of assuming a 99% efficient duct system, a 3% overestimate of efficiency improvement. The energy savings declined, and CCEs increased for every measure except the intermittent ignition device (which is independent of furnace efficiency).

5.4f The Absolute Size of an Error Will Diminish as It Propagates through a Sequence. Once an error has occurred, subsequent conservation measures offset small portions of the error. The relative size of the error may rise or fall, depending on the types of measures, but the absolute size will decrease. The error can be reduced substantially when there are efficiency improvements in subsequent measures.

This concept is also illustrated in Table 5-11, where the initial error was a 4 GJ/yr overestimate of energy savings from duct insulation. At the end of the sequence, error has been reduced to 1.2 GJ/yr. (Compare "Final conditions after retrofit" in the base case and in Table 5-11.)

5.4g Deletion and Insertion of a Conservation Measure. Removing a measure from a sequence allows subsequent measures to save more energy. As a result, subsequent measures have lower CCEs (or unchanged ones if there is no interdependence). In this way, the supply curve of conserved energy is "conservative;" it illustrates energy savings under the strictest economic scenario by assuming that all cheaper (lower CCE) measures have already been implemented. Table 5-12 shows the consequences of deleting duct insulation, the first measure in the sequence. The energy savings for most measures increase, while their CCEs drop.

Implementing a measure earlier than shown in the sequence is similar to deleting all measures between its original and revised positions. The energy savings attributed to that measure will remain the same or, more likely, increase (causing the CCE to decrease).

**initial conditions and assumptions:**

| | | |
|---|---|---|
| energy use | = | 183.6 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 40.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. add attic insulation | 700.0 | 30.0 | 0.9 | 130.3 | 53.3 |
| 2. add wall insulation | 900.0 | 30.0 | 1.7 | 95.3 | 35.0 |
| 3. insulate ducts | 300.0 | 25.0 | 2.6 | 87.0 | 8.3 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 80.0 | 7.0 |
| 5. tuneup furnace | 65.0 | 3.0 | 3.7 | 73.6 | 6.4 |
| 6. weatherstrip | 300.0 | 10.0 | 4.1 | 64.1 | 9.5 |
| 7. install storm windows | 800.0 | 20.0 | 4.9 | 50.9 | 13.2 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 6.4 | 46.9 | 4.1 |

**Final conditions after retrofit:**

| | | |
|---|---|---|
| energy use | = | 46.9 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 7.4 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.72 |
| discount rate | = | 5.0 % per year |

Table 5-10. The optimal sequence of conservation measures when an error is made in initial energy use. Here, the conduction loss through the attic was erroneously assumed to be 40 GJ/year rather than 20 GJ/year. This caused a major reordering of the sequence. Even conservation measures unrelated to the attic heat loss, such as storm windows, display different energy savings.

**initial conditions and assumptions:**

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. insulate ducts | 300.0 | 25.0 | 1.2 | 132.9 | 17.4 |
| 2. add wall insulation | 900.0 | 30.0 | 1.9 | 102.2 | 30.7 |
| 3. add attic insulation | 700.0 | 30.0 | 1.9 | 78.7 | 23.4 |
| 4. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 71.7 | 7.0 |
| 5. weatherstrip | 300.0 | 10.0 | 3.9 | 61.7 | 10.0 |
| 6. install storm windows | 800.0 | 20.0 | 4.6 | 47.8 | 13.9 |
| 7. tuneup furnace | 65.0 | 3.0 | 6.2 | 44.0 | 3.8 |
| 8. thermostat set back, 22->20 | 200.0 | 10.0 | 7.4 | 40.5 | 3.5 |

**Final conditions after retrofit:**

| | | |
|---|---|---|
| energy use | = | 40.5 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.74 |
| discount rate | = | 5.0 % per year |

Table 5-11. The optimal sequence of conservation measures when an error is made in the calculation of energy savings for one measure. Here, an error in the duct-insulation algorithm incorrectly overestimated the measure's savings. As a result, the energy savings for all subsequent measures declined and their CCEs increased.

**initial conditions and assumptions:**

| | | |
|---|---|---|
| energy use | = | 150.3 (GJ/year) |
| thermostat setting | = | 22.0 (deg. C) |
| attic conduction loss | = | 20.0 (GJ/year) |
| wall conduction loss | = | 35.0 (GJ/year) |
| infiltration loss | = | 18.0 (GJ/year) |
| window loss | = | 13.0 (GJ/year) |
| pilot loss | = | 7.0 (GJ/year) |
| furnace syst.effic. | = | 0.60 |
| discount rate | = | 5.0 % per year |

| measure name | Cost ($) | Life (years) | CCE ($/GJ) | Energy Use After Measure | Energy Savings |
|---|---|---|---|---|---|
| 1. add wall insulation | 900.0 | 30.0 | 1.7 | 115.3 | 35.0 |
| 2. add attic insulation | 700.0 | 30.0 | 1.7 | 88.6 | 26.7 |
| 3. intermittent ignit. device | 150.0 | 10.0 | 2.8 | 81.6 | 7.0 |
| 4. weatherstrip | 300.0 | 10.0 | 3.4 | 70.2 | 11.4 |
| 5. install storm windows | 800.0 | 20.0 | 4.1 | 54.4 | 15.8 |
| 6. tuneup furnace | 65.0 | 3.0 | 5.5 | 50.1 | 4.4 |
| 7. thermostat set back, 22->20 | 200.0 | 10.0 | 6.5 | 46.1 | 4.0 |

**Final conditions after retrofit:**

| | | |
|---|---|---|
| energy use | = | 46.1 (GJ/year) |
| thermostat setting | = | 20.0 (deg. C) |
| attic conduction loss | = | 3.7 (GJ/year) |
| wall conduction loss | = | 12.9 (GJ/year) |
| infiltration loss | = | 10.3 (GJ/year) |
| window loss | = | 3.2 (GJ/year) |
| pilot loss | = | 0.0 (GJ/year) |
| furnace syst.effic. | = | 0.65 |
| discount rate | = | 5.0 % per year |

Table 5-12. The optimal sequence of conservation measures when a measure is deleted. Here, duct insulation has been deleted. Most measures save more energy (than in the base case) and have lower CCEs. Note that the final energy use is higher when the measure is deleted.

Inserting a new conservation measure produces exactly the opposite results. All subsequent measures will save less (or the same) energy and have higher costs of conserved energy. The magnitude of the adjustment depends on the interdependence of the measures. Inserting an efficiency-improvement measure, such as duct insulation, will trigger considerable changes.

5.4h A Step on the Supply Curve Represents a Distribution of Costs of Conserved Energy.

One of the "heroic assumptions" needed to create conservation supply curves (or any other estimate of conservation potentials) is the belief that a large stock can be modeled by a single, "average," or "representative" case without introducing large errors. Yet the energy equipment within a stock will never be perfectly homogeneous. For example, variations in the performance of the furnace, insulation, and building envelope will cause "identical" homes to require different amounts of heat to maintain a given inside temperature. In reality, the initial energy use and energy savings from measures will consist of distributions rather than single numbers. Princeton's study of nearly identical townhouses in Twin Rivers showed a wide variation in energy use. About 20% of identical, interior townhouses had energy consumptions greater than one standard deviation from the mean.[4]

A single unit's CCE may be much higher or lower than the average shown on the curve, and may even exceed the next step. The optimal order of measures for any single unit may not be the order shown on the curve, but prediction becomes more accurate as several units are treated together.

5.4i An Uncertainty Principle. In the process of aggregating energy savings, one assumes that the energy savings described for one case typify the entire stock to which the measure can be applied. Put another way,

$$\text{aggregate energy savings} = \text{eligible stock} \times \text{average energy savings} \;.$$

The energy savings for one unit can be estimated accurately because the conditions can be carefully controlled. If the savings are based on computer simulation, the initial operating conditions and specifications of the measure will be clearly defined. In the case of data obtained through direct measurement, some details may not be known, but at a minimum one can state that an estimate is accurate "for the conditions in the building specified."

The great precision available at the single-unit scale contrasts with the uncertainty regarding the stock. The stock is heterogeneous; and even if the stock's average energy use is identical to that of the single unit modeled, a random unit within the stock will certainly differ in size, initial level of insulation, operating hours, or temperature. One goal is to keep the distributions fairly narrow so that the average case modeled reasonably represents the stock.

A kind of uncertainty principle applies here. The more precisely one specifies a conservation measure (to more accurately know its energy savings), the less precisely one knows the stock to which the measure applies.

Consider the tentative measure description, "Add R-11 wall insulation to all gas-heated, Northern California houses." The number of houses eligible for this measure is fairly well known. However, the range of energy savings due to this measure could be enormous. Variables such as house size, thermostat setting, furnace efficiency, and site orientation will certainly affect the energy savings. Choosing specific conditions for modeling the average case is very difficult, so the estimate of unit energy savings will be very uncertain.

This measure could be defined more accurately by disaggregating it: "In all 1500-degree-day regions, add R-11 wall insulation to single-story houses having floor areas of 180 square meters, a furnace efficiency of 70%, and a constant 22°C thermostat setting." Although the estimate of unit energy savings will now be much more accurate, the number of homes fitting this description is not known to nearly the same precision as for the first, more general measure.[5]

The same principle applies to estimating the initial baseline consumption by an end use. The more precisely one defines the stock, the less precisely one can determine initial energy use.

The uncertainty principle is not a permanent limit; rather it serves to direct efforts to improve energy data. It is unproductive to refine the calculations for a single unit when corresponding refinements in the stock data are not possible.

From a policy perspective, maximum disaggregation is best since different policies might be applied to various parts of the stock. Yet the uncertainty principle implies that there are limits to the benefits of disaggregation. The CCEs will be accurate but the aggregate energy savings may be wildly off, and therefore lead to spurious conclusions. This approach may nevertheless be useful for policy purposes: to emphasize the economic potential for a measure within a certain substock, one might sacrifice precision in aggregate savings in order to advertise the measure's low CCE. The cheapest measure (in spite of uncertain regional potential) might justify special policies. For example, houses having cathedral ceilings are treated as "uninsulatable" and ignored in many insulation programs. But these houses can be insulated very cheaply in conjunction with re-roofing. (Therefore the rate at which the homes acquire insulation will depend on the life expectancies of the roofs.) The energy savings for this measure can be easily, and quite accurately, calculated. Unfortunately, there are no estimates for the number of houses having cathedral ceilings in a given region. The stock may be guessed, and the measure listed on the supply curve, simply to alert policy-makers that such a measure exists and is worth considering.

Supply curves of conserved energy are still evolving. No doubt more "tips" and theorems will arise as this evolution proceeds. Still, the concepts presented in this chapter should give the reader (and user of supply curves) some quantitative feeling for the sensitivity of supply curves of conserved energy.

## 5.5 References and Notes

1. Payments are assumed to occur at the end of the time period. If they are assumed to occur at the beginning, then an additional (1 + d) will appear in the denominator. This lowers the cost of conserved energy.

2. By ensuring that the sequence began with an efficiency-improvement measure, the initial conditions and algorithms used in this model exaggerate sensitivity, but are nevertheless fairly reasonable. The 66% reduction in energy use corresponds well with Princeton's retrofit experience at Twin Rivers. Robert H. Socolow, ed., Saving Energy in the Home (Cambridge, MA: Ballinger Publishing Co., 1978).

3. Solar Energy Research Institute, A New Prosperity. Andover, MA: Brick House Publishing, Co., 1981. p. 48.

4. Robert H. Socolow, ed., Saving Energy in the Home (Cambridge, MA: Ballinger Publishing Co., 1978), p. 42.

5. The converse can occur also. In some cases, there is better stock data than data for unit energy savings. Prototype energy-efficient equipment may have been developed in only a few sizes. The savings are known for just those sizes, whereas the stock data may be broken into many more sizes. For example, development of prototype energy-conserving refrigerators has focused on the most popular size. The stock data, however, is disaggregated into size and features. Clearly the single prototype cannot be used to represent the entire stock, yet prototypes for other sizes and features have not been developed.

# Chapter 6: A MORE CAREFUL INSPECTION OF CONSERVATION SUPPLY CURVES

# 6. A MORE CAREFUL INSPECTION OF CONSERVATION SUPPLY CURVES

Supply curves of conserved energy were first conceived as a visually appealing means of presenting the potential for energy conservation. The competition was poor -- large and complicated tables of numbers -- so the success of the curves was no surprise. However, the concept has been extended so that supply curves now also represent an accounting framework for the economics and potential of conservation. The expanded role results partly from the more careful definition of the cost of conserved energy. The CCE is not yet an accepted investment statistic, but its characteristics and behavior (described in chapters 4 and 5) are now understood.

At the same time, the use of supply curves has aided in establishing energy-accounting principles. Consistent accounting is essential if a supply curve of conserved energy is to be compared to one of conventional energy supplies. Errors in estimating or double-counting can be minimized, or at least their consequences described in terms of their effect on the supply curve. These principles are necessary to permit the comparison, or even combination, of supply curves. In other words, the conservation supply curve possesses sufficiently well defined properties and behavior to qualify as a concept. Supply curves allow us to speak of conservation as a generalized approach rather than an agglomeration of measures. We can now think of conservation instead of increasing motor efficiency and insulating homes as we would think of "increasing oil supplies" instead of drilling in individual oil fields, such as Prudhoe Bay, North Sea, or Texas.

The evolution of a consistent accounting framework has produced supply curves of conserved energy that can be used as policy tools. Policy-makers must understand the limitations of the supply curves to minimize their misapplication. Some of the policy applications and pitfalls are described in Chapter 3.

As the definition of a supply curve of conserved energy crystallizes, another question arises: does this concept provide any new insights into traditional economic approaches to the supply and demand for energy? The notion that energy can be supplied by using less of it is a new perspective. Supplying energy by using less also creates practical difficulties in relation to traditional theories. For example, we have ignored the problem of finding a demand curve that will "cross" with a conservation supply curve. This in turn affects the way in which the comparison price is selected. In this chapter, properties of the conservation supply curve are discussed in the context of the traditional demand-supply framework.

## 6.1 The Reserves of Conserved Energy

Many energy-conservation measures are implemented as natural responses to higher energy prices. Such actions reflect part of the consumer behavior represented in a demand curve. In contrast, the reserves of conserved energy consist of measures the implementation of which is blocked by market failures. Put another way, the reserves represent a segment of consumer demand for energy that is price-inelastic. In Chapter 1, we presented evidence suggesting that nearly every consumer in the energy marketplace is affected by one or more of these market failures. These failures include economic asymmetries between the energy supplier and the consumer (discount rates and lifetimes of investments), separation of costs and benefits (landlord-tenant impasses), and indirect costs of maintaining a reliable and secure energy supply system (borne by the government and utilities). Finally, the reserves of conserved energy include measures that under normal circumstances would be implemented very slowly.

These reserves are not fixed. A few market failures are being eliminated as energy costs become more significant. Some builders now offer energy-efficient homes equipped with efficient appliances. Energy consumption data are now more easily obtainable (and standardized) to permit a better-informed purchase of autos, appliances, and equipment.[1] Conservation tax credits also encourage--or are aimed at encouraging--more conservation activity. In spite of this progress, most of the potential for conservation will remain untapped.

## 6.2 Finding a New Equilibrium

How does the introduction of conservation supply curves change the equilibrium price and quantity of energy consumed? Ordinarily, increasing supplies lowers equilibrium price and increases the quantity consumed. This is also the case when supply curves of conserved energy are included. But conserved energy differs from ordinary energy supplies because its inclusion results in a lower energy consumption.

Consider the supply and demand for electricity without conservation supply curves, as is shown in Figure 6-1. Electricity is supplied by a variety of generation sources: hydro, coal, oil,and nuclear. Each has a supply curve as shown. The slope of the demand curve reflects consumer responses to changes in electricity prices. With increasing prices, some consumers will invest in conservation measures; others will curtail their use through sacrifice or changes in behavior. Still others -- those restrained by the market failures described in Chapter 1 -- will do nothing. If an increase in population leads to an increase in electricity demand, the price will rise as demand shifts up the supply curve (D to D′ in Figure 6-1).[2]

Now consider the impact of including a conservation supply curve. Such a curve might suddenly appear in several ways. For example, a public utility commission could give a utility company the authority to "rate-base" conservation measures, that is, treat them as they would investments in power plants. The utility immediately has access to a new, and possibly inexpensive, supply it can factor into its supply curve. This scenario closely parallels the impact of the PURPA legislation, which required utilities to purchase electricity from small suppliers.[3] Proposed legislation in California would require utilities to invest in cost-effective conservation measures (and include those costs in the rate base) before building energy supply facilities.[4]

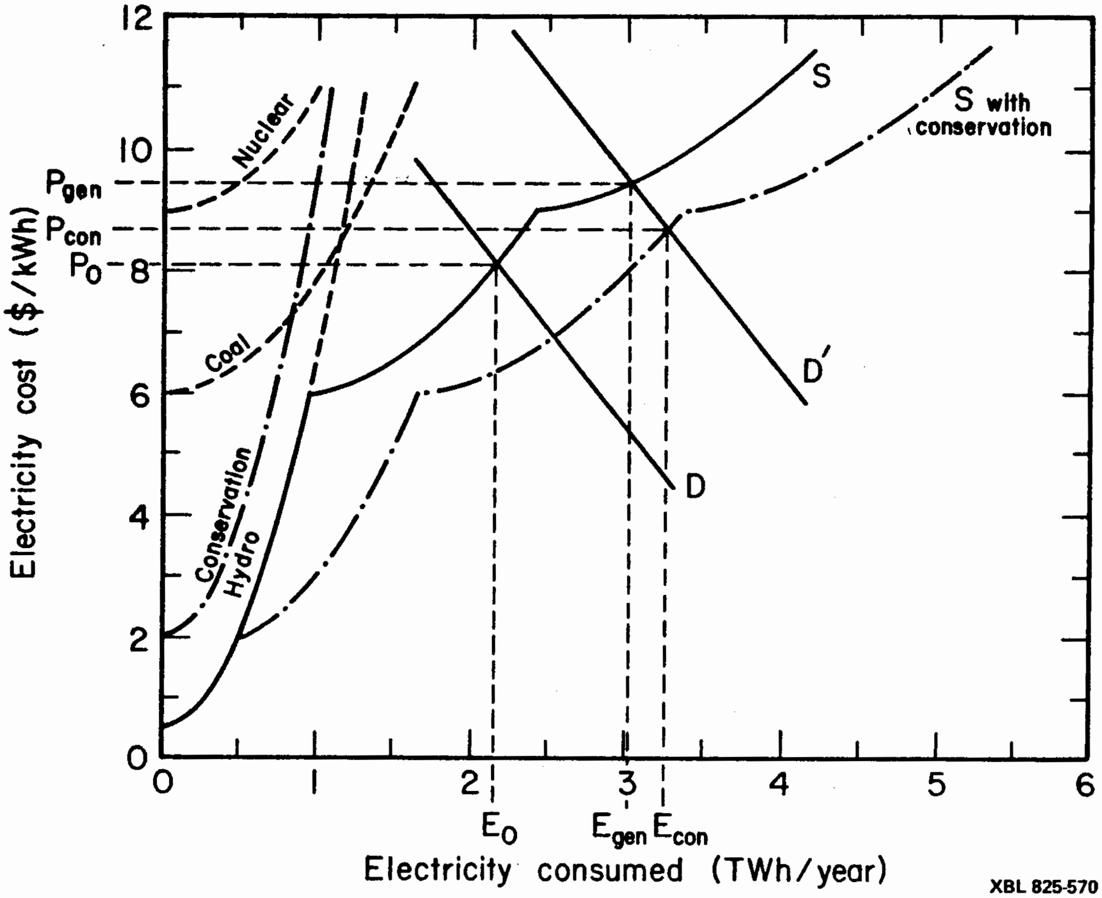


Figure 6-1. Inclusion of the supply curve of conserved energy after an increase in demand (on the right hand side of the Figure). Demand increased from D to D′ (perhaps as a consequence of population growth). Normally, the equilibrium price would have risen to $P_{gen}$ and $E_{gen}$ would have been supplied. However, if the utility can invest in conservation, it will operate with a supply curve S (with conservation). Consumers will use the equivalent of $E_{con}$ at an equilibrium price, $P_{con}$, even though actual electricity generated will remain $E_{gen}$.

The supply curves for an electric utility are on the left hand side of the Figure. Each source would be exploited until the cost of supply equalled the equilibrium price. Using $P_{gen}$ instead of $P_{con}$ as the equilibrium price leads to an overinvestment in energy supplies, including conservation. With conservation included as a supply, the nuclear option would no longer be profitable.

The new supply curve, including conservation, is shown as a dotted line in Figure 6-1.[5] The equilibrium price is $P_{con}$ instead of $P_{gen}$. At this lower price, consumers demand more electricity than otherwise. The utility actually generates $E_{gen}$, but the equilibrium is at $E_{con}$. $E_{con}$ represents the consumption of real electricity and conserved electricity (a value of concern only to bored energy analysts). The difference, $E_{con} - E_{gen}$, is the electricity supplied through conservation.

Two points are needed to define the equilibrium: one for price, and another for quantity. If we want to know the "effective electricity consumed," i.e., generated plus conserved, then one point suffices. A utility, however, still needs to know how much electricity to generate, hence the two-point analysis.

Careful examination of the disaggregated supply curves in Figure 6-1 shows that an earlier decision rule must be revised. Recall the decision rule: "Invest in all measures having a CCE less than the energy price." This established a cut-off line on the supply curve of conserved energy. But including conserved energy in the supply curve results in a lower equilibrium price than would have been used as the cut-off. An over-investment in conservation would occur. Such an over-investment occurs with conventional supplies; Figure 6-1 shows how the entire nuclear commitment constitutes an over-investment.

Is this over-investment significant? In at least one study, yes. The SERI study initially used the marginal electricity price as the cut-off price for the supply curves.[6] However, so much electricity was shown as conserved that no new plants would be needed; indeed, some existing plants could even be phased out. The lower, average electricity price was more appropriate than the marginal price in these conditions. Most potentials studies have ignored the over-investment problem. Yet, it is not necessarily a serious omission. Conservation supply curves typically rise quite sharply near the average energy price; shifting the cut-off line from the marginal to the average price produces only a small change in the economic reserves of conserved energy. (Compare the potential shown in Figure 3-1 at 10 cents/kWh--a reasonable marginal price--to 6 cents/kWh--the average price.) The economic reserves of conserved energy fell only slightly in the SERI study, after switching from the marginal to the average price.[7]

Several features of the supply curve of conserved energy make the equilibrium described above and in Figure 6-1 inaccurate. These are discussed below.

## 6.3 The Level-of-Service Bias

The assumption that the level of service will remain the same overpredicts the potential savings from conservation measures. Recall that the level of service is held constant throughout a sequence of measures, even though the cost of conserved energy spans a wide range.

Consider the case of insulating an apartment for which the tenant pays the heating bills. At higher energy prices, a tenant may cut his heating bill by lowering the room temperature -- that is, he may accept a lower level of service. However, the estimated conservation potential for insulation would have been based on the original, higher, room temperature. The savings attributed to the measure will be greater than would in fact occur. On the other hand, if the landlord paid the fuel bills, the tenant might not have lowered the temperature, and the initial savings estimate would have been correct. In general, the supply curve of conserved energy will overestimate the technological potential when consumers have the ability and willingness to control the levels of services.

Levels of service are not always easy to adjust. For example, once a refrigerator is purchased, little can be done to reduce the level of service to significantly lower electricity consumption. Some end uses have limited flexibility in the level of service: commercial buildings might lower lighting levels and permit greater thermostat fluctuations, but they are often constrained by complaints of staff or customers.

A supply curve of conserved energy could be based on any level of service, but it is simplest to use the current level. This is also much more enlightening from a policy perspective because it maintains a consistent starting point; namely, current energy use and current levels of service. This is also the only reasonable assumption when comparing conserved energy to conventional supplies because the type of fuel does not influence consumer behavior.

## 6.4 The Conversion of Conserved Energy to Increased Amenities

In some instances, consumers will not be satisfied with the current level of energy service. Instead of saving energy, they may choose to convert it to a higher level of service. For example, following the insulation of his house by the utility or government, an occupant may discover that he can now maintain a more comfortable temperature with no change in energy use. Moreover, he may find the increased comfort preferable to the energy savings. Some weatherization programs have reported disappointing energy savings, possibly because the participants converted much of the energy savings into increased amenities.[8] The purchase of fuel-efficient automobiles is another example. Here, consumers appear to have converted some of the fuel savings to driving greater distances, e.g., a higher level of service.

Note that this effect does not offset the level-of-service bias mentioned earlier. There, the original level of service, such as room temperature, was adequate or could even be reduced. Here, the original level of service (the distance traveled) was inadequate and would be increased if the opportunity existed. The first effect is a result of higher energy prices; increasing amenities is a result of conservation measures.

It is impossible to predict what fraction of energy savings will be converted to increased amenities; it clearly will depend on the end use. It will be greatest where the current level of service is inadequate and smallest where consumers are satisfied with current amenities.

## 6.5 Economic Perspectives

Several actors may construct conservation supply curves. A consumer may choose to construct his own curve for a house or factory; a utility or government agency may construct one for the same house or factory. Even though the measures on the curve are identical, the economic assumptions, or "perspectives," will differ. For space-heating conservation measures in a house, a consumer might calculate a measure's cost based on installing the measure himself, while a utility would probably use the contractor cost plus the cost of administering a conservation program. The consumer will amortize the investment over any time he chooses, perhaps the time he expects to own the house, whereas a utility would amortize the investment over the measure's physical lifetime. Finally, the consumer may assume a very high discount rate, perhaps greater than 50%, while the utility would use a much lower one.

The costs of conserved energy as produced by these different economic perspectives vary greatly. Since there is no single "correct" economic perspective, there is no single "correct" supply curve of conserved energy. Instead, there are several supply curves, each revealing its own economic perspective. It is crucial to choose a perspective and apply it consistently throughout an analysis. In addition, the meaning of a supply curve, and its interpretation, will depend on the perspective adopted. Some economic perspectives are presented below.

The simplest perspective to adopt is your own.[9] If you are a consumer who also generates his own electricity, you might use a conservation supply curve to determine the best mix of supplied and conserved electricity. You determine the cost and decide who will install the measures. Likewise, you choose the amortization time and discount rate. Finally, you can adjust the energy savings for any anticipated changes in use patterns. As usual, the cut-off price is determined by the cost of supplied energy.

Constructing a supply curve having the more general "consumer perspective" is more difficult; it is like constructing a conservation supply curve for a neighbor whom you do not know very well. Here, costs and amortization times for the measures must be guessed: will he install the measures himself, or hire a contractor? how long does he expect to live in the house? A discount rate would be based on apparent behavior and his ability to obtain credit. The comparison price would be that of the avoided energy.

The supply curve from a consumer perspective will describe some market failures. Here, the consumer has perfect information and acts (from his perspective) rationally. On the other hand, the discount rate may be higher, and the amortization time shorter, than that assumed by a utility. (Conservation measures with separated benefits and costs will not appear in this perspective.)

A utility perspective will include the cost of implementing a conservation measure plus any program costs. This perspective might include transmission losses (if this made it comparable to supply analyses) and would use the measure's physical lifetime. Finally, the discount rate would be that used for comparable energy supply projects. This perspective would be appropriate for the type of analysis presented in Section 6.4, Finding a New Equilibrium.

A government agency contemplating the establishment of energy- conservation standards or regulations would employ a slightly different perspective. The cost would include the parts, installation, and program administration. It would employ a social discount rate and physical lifetimes. Similarly, the comparison energy price would reflect the social value of the energy, including perhaps a national security premium and pollution costs.

## 6.6 Supply Curves of Conserved Energy ... in Practice

Earlier sections detailed the kinds of market failures that create reserves of conserved energy. In practice it is impossible to completely separate cases where the market works and where it fails. First, there is no way to predict which consumers have adequate information to make rational decisions. Even then, we cannot easily differentiate between consumers who are using a 8% discount rate (that is, a rate close to that used on the supply side) and those using a 75% rate. Similarly, we cannot separate those consumers who amortize investments in efficient refrigerators over ten years from those who amortize them over the investment's physical lifetime.

The potentials shown in real-world supply curves of conserved energy include both market failures and successes. As a result, some of the conservation response that legitimately belongs in the demand curve (because the market is working) is stuck inside the conservation supply curve. The results can be reduced by the fractions that we expect will be implemented without intervention. For example, if we expect 20% of the single-family homes-owners to insulate their water heaters without assistance, the supply curve potential for that measure would be reduced 20%.

Thus, there are three major sources of uncertainty -- all leading to overestimates of conservation potential -- embedded in real conservation supply curves. These are 1) the conversion of conserved energy to increased amenity, 2) the unanticipated reduction in level of service, and 3) the inability to separate potentials due to market failures from energy savings that will occur due to the market operating successfully.

## 6.7 Net Energy Considerations

Implementing conservation measures will prompt new energy expenditures that call for energy-intensive materials. The residential sector, for example, will need more insulation, glass, and cement. To this extent, the supply curve describes a shift of energy use from the consumer sector to the energy-conservation industries and services sector. However, this effect will be small. Input-output analyses suggest that no more than 10% of the potential residential energy savings would be offset by new energy consumption in conservation materials and services.[10,11] The supply curves of conserved energy provide a new perspective on this often-raised non-problem.

Most conservation supply curves show large reserves of conserved energy below the current energy price. If conservation measures are implemented until the final measure's CCE equals the price of energy, the total conservation payments will be less than the initial energy payments. (See Figure 6-2 for a graphical explanation.)

What happens to the remaining dollars previously spent on energy? Presumably, these dollars will be spent on other goods and services, or saved. These new activities -- termed "respending" -- consume energy. For example, the homeowner who insulated his house may have borrowed money, with re-payment scheduled over ten years. In the first year, he saved so much energy that, not only could he pay the first loan installment, but enough remained for a midwinter plane trip to Florida. Roughly 40 cents of each dollar of the plane ticket pays for fuel, so every dollar saved in heating bills, now converted to an airplane ticket, prompts a new energy expenditure equal to about 40 cents. In this extreme example, only 60% of the energy savings shown on the supply curve really occurred; in reality, there was a transfer of energy use from the residential to the transportation sector. By turning off the heat while on his trip, the consumer saves even more, a secondary effect not considered in this example.

Input-output models of the United States' energy economy can also estimate the fate of the remaining dollars previously spent on energy. These models suggest that about 10 cents of each dollar of consumer expenditure eventually purchase energy (that is, about the same as for conservation investments).[12] In this way, the residential supply curves of conserved energy overestimate the net energy savings 10 % by ignoring transfers to the industrial, commercial, transport, and service sectors due to respending.

We can derive estimates of the potential dollars freed for other uses through investment in electricity-conservation measures in California's residential sector from Wright et al. Figure 6-2 shows the electricity conserved after 10 years, that is, at the end of the time horizon. Assuming that the comparison energy price is 8 cents/kWh, all measures up to and including #32 are economical, corresponding to 10,907 GWh/year of saved electricity. At 8 cents/kWh, consumers would avoid $873 million a year in electricity payments. On the other hand, they would pay an average of 2.3 cents/kWh for conservation investments, or $251 million per year. The difference, $622 million, or about $300 per Californian, is freed for spending on other activities.[13]

We may suppose instead that all the conservation measures have already been implemented until the CCE equals the energy price. If we then assume that energy prices rise an increment, to perhaps 8.5 cents/kWh, the net energy consequences of implementing the now-economical conservation measures are different than in the previous "catch-up" situation. The consumer would face two alternatives: either he pays for higher-priced fuel or implements conservation measures having CCEs equal to the new energy price. In the latter case, conservation may not entirely offset the higher prices, so his total bill may

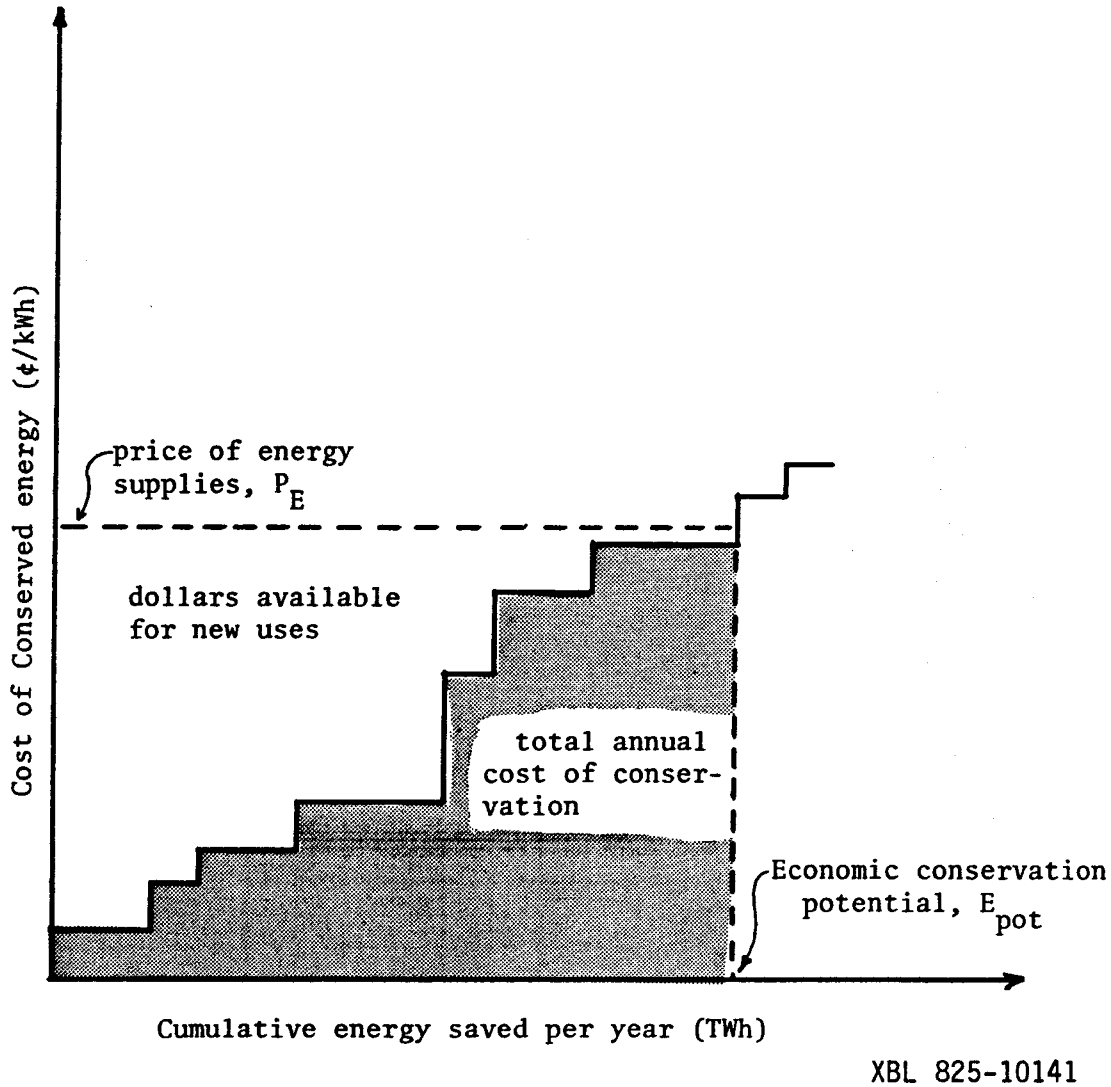


Figure 6-2. Investment in conservation liberates dollars for spending on other activities. If consumers invest up to the economic potential of conservation, they will spend \$251 million per year. This is the shaded area below the curve. Had consumers implemented none of the conservation measures, they would have paid $P_E \times E_{pot}$ = \$873 million dollars per year. The difference, that area above the curve and below $P_E$, is the money now available for spending elsewhere.

still increase. In both cases, the consumer must shift money from other activities to pay the higher energy bill. Such a shift slightly reduces energy use in other sectors.

Simply paying the higher fuel bill (i.e., no conservation investments) maintains the original level of energy use, minus the energy from canceled activities. The alternative (implementing conservation measures) will increase energy use in other sectors, but canceled activities and conservation-related energy use will offset each other. The type of activities and conservation measures will determine whether the net effect will be positive or negative. In either case, the effect is very small. The conservation supply curve will accurately predict the net energy savings for incremental advances. These second-order and third-order effects, well beyond the precision of any existing energy models, should be ignored because they only distract those responsible for setting energy policies.

## 6.8 References and Notes


1. Rectification of some market failures may lead to new ones. For example, landlords who own master-metered units are rapidly converting them to individual metering and independent heating systems. With master metering, insulation would be a worthwhile investment for the landlord, especially if the tenants used open windows as thermostats. The tenants will be more frugal with individual metering, but the landlord's incentive to insulate disappears.

2. The analysis is similar for a reduction in supplies, that is, a leftward shift of the supply curve.

3. Public Utilities Regulatory Policy Act, United States Congress, Public Law 95-617, 1978.

4. California State Assembly Bill #3442 (introduced 12 March 1982).

5. Note that this curve must be developed using an economic perspective consistent with other supply curves. In this case, it would be an electrical utility perspective.

6. Solar Energy Research Institute, _A New Prosperity_ (Andover, MA: Brick House Publishing, Co., 1981.)

7. Solar Energy Research Institute, _A New Prosperity_.

8. E.J. Soderstrom et al., _Evaluation of Conservation Programs: A Primer_ (Oak Ridge, TN: Oak Ridge National Laboratory Report ORNL/CON-76 [July 1981]).

9. A more detailed discussion of this perspective is presented in: Alan Meier, _The Cost of Conserved Energy as an Investment Statistic_, (in preparation).

10. Eric Hirst, Oak Ridge National Laboratory, Oak Ridge, TN, personal communication, 11 September 1981.

11. A rule-of-thumb applies here. If a conservation measure is cost-effective, then the energy savings will be much greater than the energy embodied in the materials and construction. This is based on the observation that, on the average, only 10% of the cost of a conservation investment pays for the embodied energy. On the other hand, the dollar savings are almost entirely energy costs. This means that a measure with a 10% dollar return on investment will generate a net energy savings after the first year. A substantial tax credit may make a conservation measure artificially cost-effective, but even a 50% tax credit results in the above measure generating a net energy savings in two years.

12. Eric Hirst and Bruce Hannon, "Effects of Energy Conservation in Residential and Commercial Buildings", Science _205_(1979): 656-661.

13. The liberated dollars available for spending on other activities as a result of implementing conservation measures is calculated as follows:

$$\text{liberated dollars (per year)} = \left( P_{energy} \times \text{total energy savings} \right) - \sum_{\text{all measures}} CCE_i \times E_i$$

where,

$P_{energy}$ = energy price

$CCE_i$ = CCE for measure 'i'

$E_i$ = energy savings for measure 'i'.

# Chapter 7: OTHER CONSERVATION SUPPLY CURVES

# 7. OTHER CONSERVATION SUPPLY CURVES

The energy market is imperfect: energy prices do not fully reflect costs, nor are all consumers able to respond to existing prices. Treating conserved energy like another supply recognizes the impossibility of eliminating these market failures, and indicates that it is cheaper to reduce demand than to obtain new supplies. Similar market distortions exist for other goods. The causes of the distortions may differ, but the gap between costs of conserving and those of supplying is identical. Three examples of markets possibly benefiting from the use of conservation supply curves are introduced below.

## 7.1 Conservation Supply Curves of Power, Water, and Pollutants

Utilities have long recognized the economies of maintaining as constant an electrical demand as possible. Generating peak power is expensive because these power plants are operated for only brief periods (and are often inefficient). Utilities have created a variety of load management programs which, until recently, were principally directed towards large customers. The rates were structured as to discourage on-peak consumption. In other words, electricity prices were adjusted to reflect the costs of generation. Implementing similar rate structures for smaller customers is more expensive and often politically impossible; for these reasons, direct utility investment in conservation is a realistic alternative. Several utilities now offer bonuses -- another way of making an investment -- to residential customers purchasing high-efficiency appliances that conserve peak power.[1]

How should the utilities best conserve peak power? What measures will save the most power, are the cheapest to implement? A supply curve of conserved power would be an effective tool for making these decisions.

The concept of conserving peak power is very similar to that of conserving electricity. Here, however, a time element enters the calculation: the conservation measure must occur while the utility experiences its peak demand. House et al., superimposed a time-of-day use pattern on the supply curves of conserved electricity estimated by Wright et al., to produce supply curves of conserved power for California.[2] Some cost-effective energy-conservation measures pay for themselves in peak-power capital savings alone; others reduce a device's peak power demand by postponing operation until an off-peak period.

Water helps provide a multitude of services, including sanitation, agriculture, and recreation. In many regions, the readily available supplies have been fully exploited, and additional supplies are much more expensive. Conservation might be considered as an alternative to new water supply facilities. Again, the questions are: what water-conservation measures are available? which save the most water? and which are the cheapest to implement?

A supply curve of conserved water could be made for California's agricultural sector, which accounts for 85% of California's total water use.[3] Here, the goal would be to maintain the same level of production with less water (analogous to assuming no change in lifestyle for residential energy). The first step would be to develop an accurate end-use breakdown for water; that is, the amounts devoted to particular crops and activities.[4] The end-use breakdown, combined with estimates of average water consumptions for major agricultural activities, would serve as the basis for estimating water savings from conservation measures. The costs of conserved water could be calculated in the same way that the costs of conserved energy were calculated. Just as with energy use, considerable anecdotal information exists, but there are few estimates of aggregate water savings for specific conservation measures. The comparison price for water supplies should be relatively simple to determine since there are numerous water-supply projects currently under construction or consideration in California. However, a statewide analysis of conservation potentials might best be compared to supply projects of a similar scale, such as the Peripheral Canal (a massive scheme to divert water from the Sacramento River to Southern California).

The supply curve of conserved water will show the extent of market failures in the agricultural sector. Certain crops or activities may appear as particularly inefficient water consumers, that is, the cost of conserving water will be much below the price paid or the marginal cost of new water supplies. The conservation supply curves also address the issue, "Is conservation a significant alternative to the development of new supplies?"

There are noteworthy differences between supplying energy and furnishing water. Building water-supply capacity is more capital-intensive than increasing energy capacity: once an aqueduct is built, the incremental cost of another cubic meter of water is negligible. The goal is to avoid building another aqueduct in the first place. With water, the cost of conserved capacity might be more useful than considering the cost of conserving a unit of water, as we would consider conserving electrical power. Needs for water <u>quality</u> also vary. Indeed, some activities can use waste water from other activities, or especially warm or saline water. This cascading of water quality is similar to cascading of energy quality which is, or could be, common in industrial energy applications (such as cogeneration). This introduces new accounting dilemmas. Clearly the precise accounting details need further exploration and definition, but the framework of conservation supply curves still applies.

A conservation supply curve might also be developed for various types of pollutants, for instance the sulfur from coal-fired power plants. This is an international problem between the United States and Canada (also between the U.K. and Scandanavian countries). While the issue is highly politicized, one solution may involve compensating for sulfur damage. It would then be to the America's advantage to reduce sulfur emissions to the point where the cost of preventing a unit of sulfur output would equal the compensation. This would establish a comparison price for a supply curve of conserved sulfur emissions. Note that here the assumption of a constant level of service would involve unchanged electrical production, which may not apply if the pollution-control equipment significantly raised the cost of the electricity generated.

Environmental Protection Agency regulations now permit new industries in polluted areas to offset their emissions by reducing those from other sources.[5] Here a "supply curve of conserved pollutants" could be drawn up to locate the cheapest means of effecting the reductions. Standard Oil of Ohio, for example, seriously considered installing emissions controls on many Los Angeles dry-cleaning facilities in order to offset the increased hydrocarbon emissions from a proposed oil terminal.[6] Presumably, "retrofit dry-cleaners" was the first measure on Standard Oil's supply curve of conserved hydrocarbons.

Conservation supply curves can be constructed wherever consumers demand services rather than a good itself. Energy, water, and pollution are examples where increasing the efficiency of converting a good to a service (or disservice) is easy to quantify and could also play a significant role in our economy.

## 7.2 References and Notes

1. These appliances include air conditioners, heat pumps, and heat exchangers for transferring waste heat from air conditioners into water-heater tanks. See: Eugene Gorzeinik, "Bonus Bucks put $ in Customers' Pockets," Electrical World (July 1981): p. 139-40, and "Newsbeat," Electrical World (March 1982): p. 13.

2. Lon House, Paul Gertner, and Ezra Amir, "Economic Assessment of Residential Retrofit Electricity Conservation Measures: Consumer and Utility Perspectives," (Sacramento, CA: California Energy Commission Staff Report No. P300-81-024 [October 1981]).

3. California State Department of Water Resources, Water Conservation in California, Bulletin No. 198, May 1976, Dept. of Water Resources, Sacramento, CA.

4. California State Office of Planning and Research, The California Water Atlas, William Kahrl ed., Sacramento, California, 1978: p. 55.

5. See William Baumol and Wallace Oates, Economics, Environmental Policy, and the Quality of Life, (Englewood Cliffs, NJ: Prentice-Hall, 1979).

6. Ibid. p. 349.

Appendix: Computer Program to Produce Examples in Sensitivity Chapter

This program calculates the energy savings and cost of conserved energy (CCE) for each measure. It also ranks the conservation measures in order of increasing CCE. Initially, the program calculates the energy savings and CCE for every measure. It chooses the measure having the lowest CCE and "implements" it, that is, calculates the energy use assuming that the measure has been performed. In addition, it resets any specific values affected by that measure. For example, insulating the attic will lower the house's total energy use; after the measure is "implemented", the program resets the conduction losses through the attic.

This program can be used for any sequence of interdependent conservation measures where the measures' energy savings can be described with simple functions. It has been easily adopted to describe water-heating conservation measures and would be easy to apply to air conditioning.

This program is written in the language 'C', and runs on the Unix operating system (version 7). Note that the statements exceeding line width of paper have been continued on the next line. A "[line continued]" has been inserted wherever this occurs. These statements must be removed, and the lines rejoined, before running the program.

```
/* This program calculates the energy savings, CCE and
   orders the measures in increasing CCE.
   Each new measure is treated as a function and therefore
   requires changes in the program in several locations.
   I have inserted a dummy variable for function wherever
   you must insert information. Just search for "dummy"
   to locate the critical data entry locations.
        Some measure data is entered in a matrix at
   the beginning. This includes: the function name, the
   description of measure, its cost, and amortization time.
   Any other measure information is entered in the function.
     If the energy savings calculation requires specific
   losses or assumptions, declare and initialize them
   in the beginning. Also ensure that the new measure does
   not require restating existing measure functions.
     To run this program, use   "cc filename -lm". (The "-lm
   calls the C math library.)
                                             */


double insul(), iid(), window(), w_strip(), tuneup(), format();
double atticinsul(), setback(), ductinsul(), dummy_fxn();
double fuel_input, wall_loss, wind_loss, infil_loss;
double effic, disc_rate, attic_loss, pilot_loss, dummy_loss;
double t_stat, savings, duct_effic, furn_effic;
struct measure {
        double  (*m_f)();
        char    *m_name;
        double  m_cost;
        double  m_life;
        int     m_flag;
}
m_table[] = {
        atticinsul, "add attic insulation", 700., 30., 1,
        insul,  "add wall insulation", 900., 30.,       1,
        iid,    "intermittent ignit. device", 150., 10.,        1,
        window, "install storm windows", 800., 20.,     1,
        w_strip, "weatherstrip", 300., 10.,     1,
        tuneup, "tuneup furnace  ", 65., 3.,    1,
        setback, "thermostat set back, 22->20", 200. ,10., 1,
        ductinsul, "insulate ducts", 300.,25.,1,
        0,      0,      0., 0,  0,
        dummy_fxn, "dummy measure", 0,0,0,
};


main() {
        double cce, ccmax, cost_e(), cost, life;
        struct measure *p, *pbest;
        char *ctime();
```

```
        long tempus, time();
        int meas_no;

        attic_loss = 20.;
        wall_loss = 35.;
        infil_loss = 18.;
        wind_loss = 13.;
        pilot_loss = 7.;
        furn_effic = .69;
        duct_effic = .87;
        effic = furn_effic * duct_effic;
        t_stat = 22.;
        meas_no = 0;
        dummy_loss = 0.;
        tempus = time(0);
        fuel_input = ((attic_loss + wall_loss + wind_loss +  [line continues]
infil_loss + dummy_loss)/effic) + pilot_loss;
        savings = 0.;
                                        /*   set discount rate here    */
        disc_rate = .05;
        printf("date of run == %35s \n\n\n\n",ctime(&tempus));
        printf("initial conditions and assumptions:\n\n");
        format();

        printf("\n    measure name                       [line continues]
Cost    Life    CCE    Energy Use    Energy ");
        printf("\n                                        [line continues]
($)   (years) ($/GJ) After Measure Savings");
        printf("\n    _______________                     [line continues]
_____   _____ _____  ___________  ________\n\n");
        printf("       initial energy use                 [line continues]
                  %4.1f\n\n",fuel_input);
        for(;;)  {
                pbest = 0;
                ccmax = 1000.;
                for(p = m_table; p->m_f; p++) {
                        if(p->m_flag == 0) continue;
                        cost = p->m_cost;
                        life = p->m_life;
                        cce = (*(p->m_f))(0, cost,life);    /* trial run */
                        if(cce < ccmax) {
                                pbest = p;
                                ccmax = cce;
                        }
                }
                if(pbest == 0) break;
                cost = pbest->m_cost;
                life = pbest->m_life;
                meas_no += 1;
                cce = (*(pbest->m_f))(1,cost,life);     /* for real */
                printf("%d. %-30s %4.1f    %3.1f    [line continues]
%4.1f    %4.1f         %3.1f\n\n", meas_no,       [line continues]
pbest->m_name, cost, life, cce, fuel_input, savings);
                pbest->m_flag = 0;
        }
        printf("\n\nFinal conditions after retrofit:\n\n");
```

```
        format();
        printf("\n\n");
}

double
                        /* wall insulation measure */
insul(n, f_cost, f_life)
double f_cost, f_life;
int n;
{
        double cce, delta_e, delta_loss;
        delta_loss = .6 * wall_loss;
        delta_e = delta_loss / effic;
        cce = cost_e(delta_e,f_cost,f_life);
        if(cce < 0.) cce = -cce;
        if(n){
                fuel_input -= delta_e;
                wall_loss -= delta_loss;
                savings = delta_e;
        }
        return(cce);
}
double
                        /* intermittent ignition measure */
iid(n, f_cost,f_life)
double f_cost,f_life;
int n;
{
        double delta_e, cce;
        delta_e = pilot_loss;
        cce = cost_e(delta_e,f_cost, f_life);
        if(n){
                pilot_loss -= delta_e;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
}
double
                /* storm windows measure */
window(n, f_cost, f_life)
double f_cost, f_life;
int n;
{
        double delta_e, cce, delta_loss;
        delta_loss = .73 * wind_loss;
        delta_e = delta_loss / effic;
        cce = cost_e(delta_e,f_cost, f_life);
        if(n){
                wind_loss -= delta_loss;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
}
double
```

```
                                /* furnace tuneup measure */
tuneup(n, f_cost, f_life)
double f_cost, f_life;
int n;
{
        double delta_e,cce,delta_effic;
        delta_effic = (1/duct_effic) * ((1/furn_effic) - (1/.75));
        delta_e = delta_effic * (wall_loss +  [line continues]
attic_loss + infil_loss + wind_loss);
        cce = cost_e(delta_e, f_cost, f_life);
        if(n) {
                furn_effic = .75;
                effic = furn_effic * duct_effic;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
}
double
                        /* weatherstripping measure */
w_strip(n, f_cost, f_life)
double f_cost, f_life;
int n;
{
        double  delta_e, delta_loss, cce;
        delta_loss = .38 * infil_loss;
        delta_e = delta_loss/effic;
        cce = cost_e(delta_e, f_cost, f_life);
        if(n) {
                infil_loss -=delta_loss;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
                          /* attic insulation measure */


}
double atticinsul(n,f_cost,f_life)
double f_cost, f_life;
int n;
{
        double delta_loss, delta_e , cce;
        delta_loss = .80 * attic_loss;
        delta_e = delta_loss / effic;
        cce = cost_e(delta_e, f_cost, f_life);
        if(n) {
                attic_loss -= delta_loss;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
}
                                /* thermostat setback measure
                                   assumes outside avg temp
                                   is -3, and that the setback
```

```
                                        is 2 degrees.   */
double setback(n,f_cost,f_life)
double f_cost, f_life;
int n;
{
        double delta_loss, delta_e , cce, fraction;
        double t_out, setbk;
        setbk = 2.0;
        t_out = -3.;
        fraction = setbk / (t_stat - t_out);
        delta_loss =  fraction *( wall_loss +  [line continues]
wind_loss +  infil_loss + attic_loss );
        delta_e = delta_loss/effic;
        cce = cost_e(delta_e, f_cost, f_life);
        if(n) {
                fuel_input -= delta_e;
                savings = delta_e;
                t_stat -= setbk;
                wall_loss -= (fraction * wall_loss);
                wind_loss -= (fraction * wind_loss);
                infil_loss -= (fraction * infil_loss);
                attic_loss -= (fraction * attic_loss);
        }
        return(cce);
}

                                        /* duct insulation measure */

double ductinsul(n,f_cost,f_life)
double f_cost, f_life;
int n;
{
        double delta_effic, delta_e , cce;
        delta_effic = (1/furn_effic) *  [line continues]
((1./duct_effic) - (1./.96));
        delta_e = delta_effic * (wall_loss +  [line continues]
attic_loss + infil_loss + wind_loss);
        cce = cost_e(delta_e, f_cost, f_life);
        if(n) {
                duct_effic = .96;
                effic = duct_effic * furn_effic;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
}
                                /* cost of conserved energy calculation */

double cost_e(delta_e,cost,lifetime)
double lifetime, delta_e, cost;
{
        double pow();
        double cce, denom;
        denom =   1. - pow((1 + disc_rate), -lifetime);
        cce = (cost / delta_e) * (disc_rate/denom);
        return (cce);
```

```
}

                                 /* formatting done here for i/o */

double
format() {
  printf("    energy use              = %5.1f (GJ/year) \n",fuel_input);
  printf("    thermostat setting      = %5.1f (deg. C) \n",t_stat);
  printf("    attic conduction loss = %5.1f (GJ/year)\n",attic_loss);
  printf("    wall conduction loss  = %5.1f (GJ/year)\n",wall_loss);
  printf("    infiltration loss     = %5.1f (GJ/year)\n", infil_loss);
  printf("    window loss           = %5.1f (GJ/year)\n", wind_loss);
  printf("    pilot loss            = %5.1f (GJ/year)\n", pilot_loss);
  printf("    furnace syst.effic.   = %5.2f\n", effic);
  printf("    discount rate         = %5.1f %% per year\n", [line continue]
(100 * disc_rate));
  /* insert dummy_loss printf here */
        return;
}

                           /* Here is the dummy measure function.
                              Use it as a template and model
                              for new measures. (15 lines to
                              copy)   */

double dummy_fxn(n,f_cost,f_life)
double f_cost, f_life;
int n;
{
        double delta_loss, delta_e , cce;
        delta_loss = .539 * dummy_loss;
        delta_e = delta_loss/effic;
        cce = cost_e(delta_e, f_cost, f_life);
        if(n) {
                dummy_loss -=delta_loss;
                fuel_input -= delta_e;
                savings = delta_e;
        }
        return(cce);
}
```

The following FORTRAN program is similar to the previous It operates on FORTRAN MNF4. Note that here the matrix holds information stored by specfic variables in the 'C' version. I thank Wolfgang Luehrsen for his assistance in translating the original program into FORTRAN.

FORTRAN.PROGRAM Page 1

```
1 WORK4                      **SUBROUTINE WORK4**

     1.    000000B            SUBROUTINE WORK4
                     C
                     C        SUBROUTINE READS IN MEASURES, ORDERS THEM FOR
                     C        INCREASING CCE AND PRINTS THEM OUT
                     C
                     C        DEFINITIONS OF VARIABLES
                     C
     2.    000000B            INTEGER NHL,NHEL,NE,NM,MAXHL,MAXHEL,MAXE,MAXNM
     3.    000000B            DATA MAXHL/10/,MAXHEL/10/,MAXE/10/,MAXNM/20/
                     C
                     C        ACTUAL AND MAXIMUM NUMBER OF HEAT LOSSES, HEAT ENERGY
                     C        LOSSES , EFFICIENCIES AND MEASURES
                     C
     4.    000000B            DIMENSION RHL(10),RHEL(10),RE(10),THL(2,10),THEL(2,10),TE(2,10)
     5.    000000B            DIMENSION UHL(2,10),UHEL(2,10),UE(2,10),UT(2)
     6.    000000B            DIMENSION TT(2)
                     C
                     C        DATA AND TITLES FOR HEAT LOSSES, HEAT ENERGY LOSSES AND
                     C        EFFICIENCIES
                     C
     7.    000000B            DIMENSION CCE(20),DELOSF(20)
                     C
                     C        STORE COST OF CONSERVED ENERGY AND SAVING PER MEASURE
                     C
     8.    000000B            DIMENSION IACT(20)
                     C
                     C        KEEPS TRACK OF ALREADY APPLIED MEASURES
                     C
     9.    000000B            DIMENSION CM(20),LM(20),TM(2,20)
    10.    000000B            REAL LM
                     C
                     C        COST LIFETIME AND TITLE OF MEASURES
                     C
    11.    000000B            DIMENSION RMHL(10,20),RMHEL(10,20),RME(10,20),RMT(20)
                     C
                     C        PERCENT HEAT LOSS SAVINGS, PERCENT HEAT ENERGY LOSS SAVINGS
                     C        PERCENT(INPUT ONLY) EFFICIENCY TURN UP, THERMOSTAT SETBACK
                     C
    12.    000000B            CCEF(DI,CO,LI)=CO/DI*DISCOU/(1.-(1.+DISCOU)**(-LI))
                     C
                     C        CALCULATE COST OF CONSERVED ENERGY
                     C
                     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
                     C
                     C        CLEAR IACT
                     C
    13.    001651B            DO 5 I=1,MAXNM
    14.    001653B            IACT(I)=0
    15.    001653B          5 CONTINUE
                     C
                     C        READ HEAT LOSSES
                     C
    16.    001656B            RHL(1)=0.
    17.    001656B            READ (5,101) NHL
```

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     18.   001663B          IF (NHL.LE.0) GOTO 10
     19.   001664B          WRITE (6,201) NHL
     20.   001671B          IF (NHL.GT.MAXHL) STOP
1  WORK4                    **SUBROUTINE WORK4**
0    21.   001675B          READ (5,102) (RHL(I),(THL(J,I),J=1,2),(UHL(J,I),J=1,2),I=1,NHL)
                      C
                      C     READ HEAT ENERGY LOSSES
                      C
     22.   001722B       10 CONTINUE
     23.   001722B          RHEL(1)=0.
     24.   001722B          READ (5,101) NHEL
     25.   001727B          IF (NHEL.LE.0) GOTO 15
     26.   001730B          WRITE (6,202) NHEL
     27.   001735B          IF (NHEL.GT.MAXHEL) STOP
     28.   001741B          READ (5,102)(RHEL(I),(THEL(J,I),J=1,2),(UHEL(J,I),J=1,2),I=1,NHEL)
                      C
                      C     READ EFFICIENCIES
                      C
     29.   001766B       15 CONTINUE
     30.   001766B          RE(1)=0.
     31.   001766B          READ (5,101) NE
     32.   001773B          IF (NE.LE.0) GOTO 20
     33.   001774B          WRITE (6,203) NE
     34.   002001B          IF (NE.GT.MAXE) STOP
     35.   002005B          READ (5,102) (RE(I),(TE(J,I),J=1,2),(UE(J,I),J=1,2),I=1,NE)
                      C
                      C     READ THERMOSTAT, OUTSIDE TEMPERATURE AND DISCOUNT RATE
                      C
     36.   002032B       20 CONTINUE
     37.   002032B          READ (5,102) RT,(TT(J),J=1,2),(UT(J),J=1,2)
     38.   002047B          READ (5,102) TOUT
     39.   002053B          READ (5,102) DISCOU
                      C
                      C     READ MEASURES
                      C
     40.   002057B          READ (5,101) NM
     41.   002063B          WRITE (6,204) NM
     42.   002067B          IF (NM.LE.0) STOP
     43.   002072B          IF (NM.GT.MAXNM) STOP
                      C
     44.   002075B          DO 25 I=1,NM
     45.   002076B          READ (5,103) CM(I),LM(I),(TM(J,I),J=1,2)
     46.   002113B          READ (5,104) (RMHL(J,I),J=1,NHL)
     47.   002125B          READ (5,104) (RMHEL(J,I),J=1,NHEL)
     48.   002137B          READ (5,104) (RME(J,I),J=1,NE)
     49.   002151B          READ (5,104) RMT(I)
     50.   002156B          IACT(I)=1
     51.   002156B       25 CONTINUE
                      C
                      C     CONTROL OUTPUT OF STATUS QUO
                      C
     52.   002162B          WRITE (6,210)
     53.   002166B          IF (NHL.LE.0) GOTO 30
     54.   002167B          WRITE (6,205) (((THL(J,I),J=1,2),RHL(I),),I=1,NHL)
     55.   002207B       30 CONTINUE
     56.   002207B          IF (NHEL.LE.0) GOTO 35
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     57.   002210B          WRITE (6,205) (((THEL(J,I),J=1,2),RHEL(I),),I=1,NHEL)
     58.   002230B       35 CONTINUE
     59.   002230B          IF (NE.LE.0) GOTO 40
     60.   002231B          WRITE (6,205) (((TE(J,I),J=1,2),RE(I),),I=1,NE)
     61.   002251B       40 CONTINUE
     62.   002251B          WRITE (6,205) (TT(J),J=1,2),RT
1  WORK4                    **SUBROUTINE WORK4**
0    63.   002262B          WRITE (6,206) TOUT
     64.   002266B          WRITE (6,207) DISCOU
                      C
                      C     WRITE OUT MEASURES
                      C
     65.   002272B          WRITE (6,208)  ((UHL(J,I),J=1,2),I=1,NHL),
                           1               ((UHEL(J,I),J=1,2),I=1,NHEL),
                           2               ((UE(J,I),J=1,2),I=1,NE),
                           3               (UT(J),J=1,2)
                      C
     66.   002342B          DO 41 I=1,NM
     67.   002344B          WRITE (6,209)  (TM(J,I),J=1,2) ,
                           1               (RMHL(J,I),J=1,NHL) ,
                           2               (RMHEL(J,I),J=1,NHEL) ,
                           3               (RME(J,I),J=1,NE) ,
                           4                RMT(I)
     68.   002404B       41 CONTINUE
                      C
                      C     CALCULATE FUELIN
                      C
     69.   002406B          HLOSS=0
     70.   002406B          DO 43 I=1,NHL
     71.   002411B          HLOSS=HLOSS+RHL(I)
     72.   002411B       43 CONTINUE
                      C
     73.   002416B          HELOSS=0
     74.   002416B          DO 44 I=1,NHEL
     75.   002421B          HELOSS=HELOSS+RHEL(I)
     76.   002421B       44 CONTINUE
                      C
     77.   002426B          EFFI=1.
     78.   002426B          DO 45 I=1,NE
     79.   002431B          EFFI=EFFI*RE(I)
     80.   002431B       45 CONTINUE
                      C
     81.   002435B          FUELIN=HELOSS+HLOSS/EFFI
     82.   002437B          WRITE (6,215) FUELIN
     83.   002444B
     84.   002444B          WRITE (6,213)
                      C
                      C     CALCULATION  LOOP
                      C
     85.   002447B          DO 90 I=1,NM
                      C
     86.   002451B          EFFI=1.
     87.   002451B          DO 47 J=1,NE
     88.   002455B          EFFI=EFFI*RE(J)
     89.   002455B       47 CONTINUE
                      C
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      90.   002461B           SRLOSS=0.
      91.   002461B           DO 50 J=1,NHL
      92.   002464B           SRLOSS=SRLOSS+RHL(J)
      93.   002464B        50 CONTINUE
                         C
                         C    DETERMINE CCE FOR ALL ACTIVE MEASURES
                         C
      94.   002471B           DO 55 J=1,NM
      95.   002473B           IF (IACT(J).EQ.0) GOTO 55
1   WORK4                     **SUBROUTINE WORK4**
0                        C
      96.   002475B           DELOS1=0.
      97.   002475B           DO 51 K=1,NHL
      98.   002500B           DELOS1=DELOS1+RHL(K)*RMHL(K,J)
      99.   002500B        51 CONTINUE
                         C
     100.   002507B           DELOS2=0.
     101.   002507B           DO 52 K=1,NHEL
     102.   002512B           DELOS2=DELOS2+RHEL(K)*RMHEL(K,J)
     103.   002512B        52 CONTINUE
                         C
     104.   002521B           DELOS3=0.
     105.   002521B           DO 53 K=1,NE
     106.   002524B           DELOS3=DELOS3+SRLOSS*(1.-RE(K)/(RE(K)+RME(K,J)))/EFFI
     107.   002524B        53 CONTINUE
                         C
     108.   002536B           FRAC=RMT(J)/(RT-TOUT)
     109.   002540B           DELOS4=FRAC*SRLOSS/EFFI
     110.   002543B           DELOSS=DELOS1/EFFI+DELOS2+DELOS3+DELOS4
     111.   002546B           LIFETI=LM(J)+0.001
                         C
     112.   002551B           CCE(J)=CCEF(DELOSS,CM(J),LIFETI)
     113.   002555B           DELOSF(J)=DELOSS
                         C
                         C
     114.   002556B        55 CONTINUE
                         C
                         C    SELECTMEASURE WITH LOWEST CCE
                         C
     115.   002562B           RC=100000.
     116.   002563B           IC=0
                         C
     117.   002564B           DO 60 K=1,NM
     118.   002565B           IF (IACT(K).EQ.0) GOTO 60
     119.   002567B           IF (CCE(K).GT.RC) GOTO 60
     120.   002571B           RC=CCE(K)
     121.   002572B           IC=K
     122.   002573B        60 CONTINUE
                         C
                         C    SET MEASURE INACTIVE
                         C
     123.   002577B           IF (IC.EQ.0) GOTO 99
     124.   002600B           IACT(IC)=0
     125.   002600B           SAVING=DELOSF(IC)
     126.   002602B           FUELIN=FUELIN-SAVING
                         C
```

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```
                         C      CORRECT STATUS QUO
                         C
     127.   002604B             DO 65 J=1,NHL
     128.   002607B             IF (RMHL(J,IC).EQ.0) GOTO 65
     129.   002613B             RHL(J)=RHL(J)-SAVING*EFFI
     130.   002616B          65 CONTINUE
                         C
     131.   002621B             DO 70 J=1,NHEL
     132.   002623B             IF (RMHEL(J,IC).EQ.0) GOTO 70
     133.   002627B             RHEL(J)=RHEL(J)-SAVING
     134.   002631B          70 CONTINUE
                         C
1  WORK4                        **SUBROUTINE WORK4**
0    135.   002634B             DO 75 J=1,NE
     136.   002636B             IF (RME(J,IC).EQ.0) GOTO 75
     137.   002642B             RE(J)=RE(J)+RME(J,IC)
     138.   002646B          75 CONTINUE
                         C
     139.   002651B             IF (RMT(IC).EQ.0) GOTO 85
     140.   002653B             FRAC=RMT(IC)/(RT-TOUT)
     141.   002655B             DO 80 J=1,NHL
     142.   002660B             RHL(J)=RHL(J)*(1-FRAC)
     143.   002660B          80 CONTINUE
     144.   002665B             RT=RT-RMT(IC)
     145.   002667B          85 CONTINUE
                         C
                         C      WRITE RESULT
                         C
     146.   002670B             WRITE (6,214) I,(TM(J,IC),J=1,2),CM(IC),LM(IC),CCE(IC),
                               1 FUELIN,SAVING
                         C
     147.   002711B          90 CONTINUE
                         C
                         C      PRINT OUT STATUS QUO
                         C
     148.   002713B             WRITE (6,211)
     149.   002717B             IF (NHL.LE.0) GOTO 94
     150.   002720B             WRITE (6,205) (((THL(J,I),J=1,2),RHL(I),),I=1,NHL)
     151.   002740B          94 CONTINUE
     152.   002740B             IF (NHEL.LE.0) GOTO 95
     153.   002741B             WRITE (6,205) (((THEL(J,I),J=1,2),RHEL(I),),I=1,NHEL)
     154.   002761B          95 CONTINUE
     155.   002761B             IF (NE.LE.0) GOTO 96
     156.   002762B             WRITE (6,205) (((TE(J,I),J=1,2),RE(I),),I=1,NE)
     157.   003002B          96 CONTINUE
     158.   003002B             WRITE (6,205) (TT(J),J=1,2),RT
     159.   003013B             WRITE (6,206) TOUT
     160.   003017B             WRITE (6,207) DISCOU
     161.   003023B             WRITE (6,215) FUELIN
     162.   003027B             STOP
     163.   003030B          99 WRITE (6,212)
     164.   003033B             STOP
     165.   003034B         101 FORMAT(I3)
     166.   003034B         102 FORMAT(F5.0,4A10)
     167.   003034B         103 FORMAT(2F5.0,2A10)
     168.   003034B         104 FORMAT(16F5.0)
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```
      003034B    201 FORMAT(* NUMBER OF HEAT LOSSES*,I3)
      003034B    202 FORMAT(* NUMBER OF HEAT ENERGY LOSSES*,I3)
      003034B    203 FORMAT(* NUMBER OF EFFICIENCIES*,I3)
      003034B    204 FORMAT(* NUMBER OF MEASURES*,I3)
      003034B    205 FORMAT(* *,2A10,F7.2)
      003034B    206 FORMAT(* OUTSIDE TEMPERATURE*,F10.1)
      003034B    207 FORMAT(* DISCOUNT RATE*,F10.2)
      003034B    208 FORMAT(//,* MEASURE NAME*,9X
                        A          ,2A10,/,25X,2A10,/,30X,2A10,/,35X,2A10,/,
                        1        40X,2A10,/,45X,2A10,/,50X,2A10,/,55X,2A10,/,
                        2        60X,2A10,/,65X,2A10,/,70X,2A10,/,75X,2A10,/,
                        3        80X,2A10,/,85X,2A10,/,90X,2A10,/,95X,2A10,/,
                        4        100X,2A10,/,105X,2A10,/,110X,2A10,/,115X,2A10)
      003034B    209 FORMAT(* *,2A10,20F5.2)
      003034B    210 FORMAT(* INITIAL CONDITIONS AND ASSUMPTIONS*)
1 WORK4                 **SUBROUTINE WORK4**
0     003034B    211 FORMAT(* FINAL CONDITIONS AND ASSUMPTIONS*)
      003034B    212 FORMAT(* ERROR IN SORTING STOP *)
      003034B    213 FORMAT(* MEASURE NAME*,16X,
                        1 *COST    LIFE    CCE     ENERGY USE   ENERGY*,/,28X,
                        2 * $        Y     $/GJ    AFTER RETRO  SAVINGS*)
      003034B    214 FORMAT(* *,I3,*. *,2A10,5F8.2)
      003034B    215 FORMAT(* ENERGY USE IN GJ/Y*,F10.2)
      003034B           END
0

07600 COMPILATION -- MNF4 LEVEL 5.24     15 MAY 82 21.57.56
```

```
 NUMBER OF HEAT LOSSES  4
 NUMBER OF HEAT ENERGY LOSSES  1
 NUMBER OF EFFICIENCIES  2
 NUMBER OF MEASURES  8
 INITIAL CONDITIONS AND ASSUMPTIONS
 ATTIC LOSSES IN GJ/Y  20.00
 WALL LOSSES IN GJ/Y   35.00
 INFILTRATION LOSSES   18.00
 WIND LOSSES IN GJ/Y   13.00
 PILOT LOSSES IN GJ/Y   7.00
 FURNACE EFFICIENCY      .69
 DUCT EFFICIENCY         .87
 THERMOSTAT SETTING    22.00
 OUTSIDE TEMPERATURE      -3.0
 DISCOUNT RATE       .05


 MEASURE NAME         ATTIC LOSS IMPROVEM.
                          WALL LOSS IMPROVEM.
                               INFILTR. LOSS IMPR.
                                    WIND LOSS IMPROVEM.
                                         PILOT LOSS IMPROVEM.
                                              FURNACE EFF. IMPR.
                                                   DUCT EFF. IMPROVEM.
                                                        THERMOSTAT SETBACK
```

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```
TUNEUP FURNACE      -0.  -0.  -0.  -0.  -0.    .06-0.  -0.
DUCT INSULATION     -0.  -0.  -0.  -0.  -0.  -0.    .09-0.
ATTIC INSULATION      .80-0.  -0.  -0.  -0.  -0.  -0.  -0.
WALL INSULATION     -0.    .60-0.  -0.  -0.  -0.  -0.  -0.
INTERMITTENT I DEVIC-0.  -0.  -0.  -0.   1.00-0.  -0.  -0.
WEATHER STRIPPING   -0.  -0.    .38-0.  -0.  -0.  -0.  -0.
STORM WINDOW        -0.  -0.  -0.    .73-0.  -0.  -0.  -0.
THERMOSTAT SETBACK  -0.  -0.  -0.  -0.  -0.  -0.  -0.   2.00
ENERGY USE IN GJ/Y    150.26
MEASURE NAME             COST    LIFE    CCE   ENERGY USE   ENERGY
                         $       Y       $/GJ  AFTER RETRO  SAVINGS
  1. DUCT INSULATION     300.00  25.00   1.58  136.83   13.43
  2. WALL INSULATION     900.00  30.00   1.85  105.13   31.70
  3. ATTIC INSULATION    700.00  30.00   1.89   80.97   24.15
  4. INTERMITTENT I DEVIC 150.00 10.00   2.78   73.97    7.00
  5. WEATHER STRIPPING   300.00  10.00   3.76   63.65   10.33
  6. STORM WINDOW        800.00  20.00   4.48   49.32   14.33
  7. TUNEUP FURNACE       65.00   3.00   6.05   45.37    3.95
  8. THERMOSTAT SETBACK  200.00  10.00   7.14   41.74    3.63
FINAL CONDITIONS AND ASSUMPTIONS
ATTIC LOSSES IN GJ/Y   3.68
WALL LOSSES IN GJ/Y   12.88
INFILTRATION LOSSES   10.27
WIND LOSSES IN GJ/Y    3.23
PILOT LOSSES IN GJ/Y   0.
FURNACE EFFICIENCY      .75
DUCT EFFICIENCY         .96
THERMOSTAT SETTING    20.00
OUTSIDE TEMPERATURE     -3.0
DISCOUNT RATE       .05
ENERGY USE IN GJ/Y    41.74
```