CHAPTER 5

Energy Analysis and Life-Cycle Assessment

As individuals, as communities, and as a society, we want to make smart energy choices and investments that are cost-effective and that can help make our energy economy sustainable. To do that we must address some questions that are basic but not always easy to answer.

For example, as an individual, should I buy a hybrid vehicle or a high-efficiency refrigerator or furnace? Should I put more insulation in my attic? Should I put solar panels on my roof? To answer these questions effectively we need to know the personal financial effects of these decisions, which requires information on energy savings and investment costs. We may also wish to assess the global environmental effects of the energy options we face, and then compare them with the financial effects. This is not always easy.

As a community, should our municipal utility invest in wind farms or an energy effciency program? Should we strengthen our building energy codes or provide incentives for efficiency improvements in existing buildings? Again this requires energy and economic analysis to evaluate energy savings and costs. But we may also justify community investments if they have additional long-lasting effects, such as local economic development or reduced impacts on the local or global environment. Again, these are not easy assessments.

As a society, should we commit to greater efficiency through vehicle, appliance, or building efficiency standards? Should we accelerate use of renewable energy through a renewable portfolio standard for electricity or a requirement for greater use of ethanol fuels? How should we balance subsidies and tax incentives and disincentives for fossil fuels, nuclear, renewable energy, and efficiency?

These questions can be answered effectively only with good information on energy, economic cost-effectiveness, and environmental costs and benefits. This chapter introduces four basic analytical methods to provide the rational information on which to base energy decisions:

1. Life-cycle assessment
2. Energy analysis
3. Economic cost-effectiveness
4. Environmental assessment

Life-cycle assessment is fundamental to "sustainability analysis" and gives us a broad framework for energy analysis in terms of both time and criteria. It forces us to look at the full range of energy, economic, and environmental impacts from "cradle to grave."

Energy analysis is the first step to determine and compare energy consumption and production of different options. This can involve complex life-cycle net energy analysis, but often the most useful energy analysis is done by calculating simple energy consumption or conversion efficiency on the back of an envelope. These calculations require some boilerplate or monitored energy data, some knowledge of energy conversion (like that described in Chapter 4), some algebra, and dimensional analysis to get the units right. We can enhance these simple calculations with more elaborate methods, even computer models that incorporate more detailed data and operating assumptions, but the simple approach will be the mainstay of this book.

Economic cost-effectiveness defines energy analysis in terms of economic and financial costs and benefits. Choices among energy options require investment, and we want to use our limited financial resources wisely. Economic cost-effectiveness methods require energy analysis to know how much energy is required; the economic value of energy supplied, produced, and/or consumed; the capital and operating costs of the system option; and the time-value of money.

Environmental assessment looks beyond economic effects and determines the impacts of energy options on the natural and human environment. It can use a range of impact indicators, such as greenhouse gas and air pollutant emissions, toxic effluents, land and water requirements, human health effects, risk and uncertainty, aesthetic impacts, and ecological effects, to name a few. Some of these measures can be put in economic terms (and incorporated into economic assessment), but others cannot.

Before exploring methods of energy, economic, and environmental analysis, we first introduce some basic principles of life-cycle assessment.

5.1 Some Principles of Life-Cycle Thinking and Sustainability Analysis

Too often we make decisions based on our perceptions of costs and benefits today without thinking of costs and benefits over the long term. For example, we may think we're smart buying a 50¢ incandescent lightbulb, rather than a $2 compact fluorescent lamp, because it is cheaper. But life-cycle thinking tells us the opposite is true: the life-cycle cost of the electricity to operate the bulbs makes the compact fluorescent lamp far cheaper despite its higher initial price.

Considering both initial "capital" cost and operating cost in making decisions is the first step to life-cycle thinking. But we are interested not only in the effects of buying and using a product but also in the full costs and benefits of acquiring materials, manufacturing, transporting, installing, operating, and ultimately disposing of a product, the so-called "cradle-to-grave" costs and benefits.

We assume that the price we pay for energy and other products includes these full costs, but most often it does not. Coal-fired power is the cheapest electricity in the United States today, but the price we pay for it does not include the full costs of mining on communities; of mercury, NO_x, SO_x, and particulate emissions on human health; of CO_2 emissions on global climate change; and of ash disposal on land and water. We have tried to enact environmental regulations that integrate those costs into the costs of business, but they fall short of considering the full life-cycle costs and benefits.

Life-cycle **cradle-to-grave** thinking expands our thinking both backward and forward along the full process of product development and disposal. William McDonough and others extend this thinking further, imagining final waste products as opportunity resources to regenerate into other uses, or what they call **"cradle-to-cradle"** (see Chapter 8).

We will later apply life-cycle assessment to the following:

- "Embodied" energy or the energy it takes to develop, process, manufacture, and transport the materials used in a building or other product (Chapter 8)
- "Well-to-wheels" assessment to compare full energy, economic, and environmental costs for different transportation options from the fuel wellhead to the vehicle or passenger miles traveled (Chapter 13)
- "Gate-to-gate" assessment to compare energy and environmental costs for different materials manufacturing or processing from entry of raw materials to manufacturing or processing plant to exit of the product

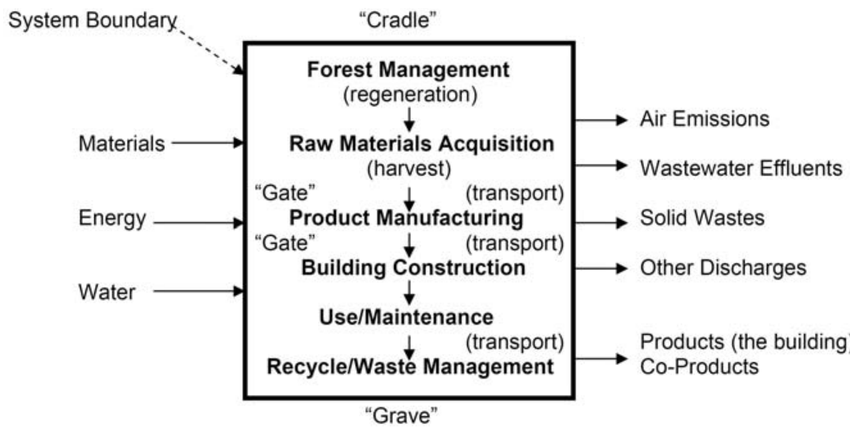
Although most energy and environmental regulations do not promote full life-cycle thinking, the recent development of voluntary certification systems and labeling systems has incorporated life-cycle costs and impacts. These include the International Organization for Standardization (ISO) 14000 family of standards for environmental management systems (EMS) for industry, the United States Green Building Council's LEED green building certifications, and a large number of green labeling systems that are popular in Europe. ISO 14001 certificates increased by 37% in 2004 to more than 90,000 in 127 countries. The protocol's prescribed standards call for extensive use of life-cycle assessment.

The process of life-cycle assessment. Life-cycle analysis assesses the performance of an activity or product over its life cycle. Measures of performance include energy use, economic cost, social effects, and environmental impact. ISO 14000 standards specify a four-step process:

1. Define goals and scope, including system boundary and impact indicators.
2. Inventory impact activities.
3. Assess impacts.
4. Evaluate and interpret results.

The heart of the process is inventory and assessment. Life-cycle inventory involves detailed tracking of all the flows in and out at various stages of the system from cradle to grave. Figure 5.1 shows the system of wood products for house construction from cradle to grave including inputs and outputs. "Gate-to-gate" addresses flow in and out for product manufacturing only.

figure 5.1 **Life-Cycle Inventory and Analysis**



This life-cycle inventory and analysis uses an example of wood products for house construction.

Source: adapted from CORRIM, 2005

Because of the number and complexity of the processes involved and the lack of detailed information, this is not an easy task. It is simplified by focusing on a few impact indicators, such as energy used, carbon emissions, and pollutant emissions. These indicators are given as the product of inventory data (quantity of material) and impact coefficients or characterization factors (impact per quantity):

Eq. 5.1 **Inventory data (e.g., lb steel) × Impact coefficient (e.g., lb CO_2/lb steel) = Impact indicator (e.g., lb CO_2)**

This is simple enough, but the challenge is finding accurate inventory data and reliable coefficients. We discuss some of these in Section 5.5.

5.2 Energy Analysis

Energy analysis begins by applying the principles of energy engineering to measure, estimate, or predict energy consumption and energy efficiency. For example, in Chapter 6 we will learn how to predict the heat loss for a building during winter using the laws of heat transfer, information on the size and material envelope of the building, and how cold the winter is at our location. We can use that information to calculate heating fuel requirements and compare those requirements for different assumptions of building insulation and materials to inform our choice of building design or whether we want to add insulation or a high-efficiency furnace.

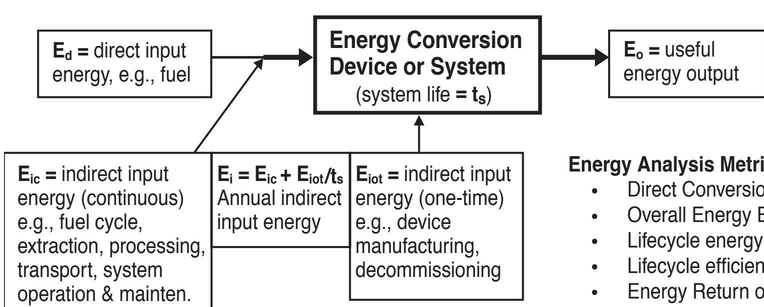
In addition, we can use "boilerplate" specifications on the efficiency of lightbulbs, automobiles, air conditioners, refrigerators, and other consumer products, to calculate the operating energy requirements and useful energy outputs. We can use that energy information to calculate cost-effectiveness and environmental impacts so we can make smart choices about the products we buy and use.

We can also use energy analysis to calculate the energy it takes to produce energy. This is the energy we need, for example, to grow corn and process it into biofuel ethanol; to extract, transport, and refine Persian Gulf petroleum into gasoline at the pump; or to manufacture and install photovoltaic modules to produce electricity. By comparing input energy including indirect inputs to output energy, we can understand the viability of energy options. If it takes more energy to produce energy than the energy we get out, we should take pause, unless perhaps in the process we can replace depletable oil or carbon-emitting fossil fuels with some type of renewable energy.

Most of this book is on applications of energy analysis, and it is useful here to give an overview of the various measures used. Ultimately, we want useful energy (and the functions it provides) from our energy sources and systems, and we want to know what it takes in energy, dollars, and environmental costs to get it. In general, energy analysis compares useful energy outputs to necessary energy inputs, either by fraction (division) or difference (subtraction). **Net energy analysis** goes further by assessing indirect energy inputs. Two things to be wary of in energy analysis: (a) you must pay careful attention to units of energy and time by using dimensional analysis, and (b) you must pay careful attention to time period because some energy outputs and inputs are continuous and some are one-time only. Often a period of one year (annual output and input) is used as the time unit of analysis.

Before discussing specific metrics used in energy analysis, we need to define some terms. Figure 5.2 helps define the terms and introduces the metrics used in energy analysis of a conversion device or system. The figure is a useful reference as we discuss each metric.

figure 5.2 Terms and Metrics Used in Energy



Energy Analysis Metrics:

- Direct Conversion Efficiency = $\eta = E_o/E_d$
- Overall Energy Efficiency = $\eta^* = E_o/(E_d+E_i) = E_o/(E_d + E_{ic} + E_{iot}/t_s)$
- Lifecycle energy: Output: t_sE_o Input: $t_s(E_d + E_{ic}) + E_{iot}$
- Lifecycle efficiency = $\eta_{ic}^* = t_sE_o/(t_s(E_d + E_{ic}) + E_{iot}) = E_o/(E_d + E_{ic} + E_{iot}/t_s)$
- Energy Return on Energy Investment (Net Energy Ratio) = **EROI** = E_o/E_i
- Energy Payback Time = **EPBT** = E_{iot}/E_o
- Fossil Fuel Ratio = $E_o/ (E_d + E_i)_{Fossil\ Fuels}$
- Net Energy Value (Energy Balance) = **NEV** = $E_o - E_i$

E_o = **useful energy (or power) output,** usually energy/time (e.g., energy/year)
E_d = **direct input of energy (or power) during operation** (e.g., fuel and/or electricity direct inputs at point of use, usually energy/time, e.g., energy/year)
E_i = **indirect input of energy (or power)** used to produce and transport to point of use (a) the conversion device (one-time cost) and (b) the direct input energy or power (continuous cost)

E_{ic} = **continuous energy costs** is usually given as energy/year.

E_{iot} = **one-time energy costs** is given by one-time energy, but can be converted to annual energy by dividing by lifetime of system in years to get energy/year. In other words,

$$E_i = \frac{E_{ic} + E_{iot}}{t_s}$$

where E_{ic} = continuous indirect energy inputs (energy/year)
E_{iot} = one-time indirect energy inputs (energy)
t_s = lifetime of system (years)

In previous chapters, we discussed mostly E_o, the useful energy output, and E_d, direct input energy or the fuel or energy input to an energy conversion system. However, it takes energy to make the direct input energy and the conversion systems we use, and "indirect input energy" tries to take that into account. For example:

- For a diesel generator, the direct input energy (E_d) is the diesel fuel. The indirect input energy (E_i) includes the energy required to extract, refine, and transport petroleum and its diesel product to the site of the generator as well as the energy required to manufacture the generator, transport it to sale, and transport it to the site of use. The indirect input energy of the fuel is a continuous cost (E_{ic}), whereas the indirect input energy to make the generator is a one-time cost (E_{iot}).
- For a photovoltaic battery system, the direct input energy is sunlight, essentially free, so $E_d = 0$. The indirect energy input is the energy required in the manufacture of the photovoltaic modules, batteries, and other components and their transport and installation on site, a one-time cost (E_{iot}).

The following sections describe each of the energy analysis metrics given in Figure 5.2, beginning with our old favorite, direct energy conversion efficiency.

5.2.1 Direct Conversion Efficiency (η)

Direct conversion efficiency is the most useful metric of efficiency and performance for energy system assessment. It describes the efficiency of a system to convert direct input energy to output energy.

Eq. 5.2 $$\textbf{Direct conversion efficiency} = \eta = \frac{E_o}{E_d} \quad 0 \leq \eta \leq 1$$

This metric is especially useful to compare options when we start and end at common points in the energy conversion process. For example, we can compare the cumulative efficiencies from "power plant to wheels" of a fuel-cell car with electric grid electrolysis for hydrogen versus an all-electric car with electric grid charging of lithium-ion batteries. We can find cumulative direct conversion efficiency by multiplying each component efficiency from the same start point (power plant) to the same end point (energy to the wheels). This is similar to how we determined the efficiency of a small hydro plant in Solution Box 4.2.

The third column of Table 5.1 gives component efficiencies for the two systems. Cumulative efficiencies are simply the product of component efficiencies. What is the cumulative efficiency of each option?

$$\eta = \eta_{cumulative} = \textbf{Product of component } \eta$$

Fuel-cell car:

$$\eta_{cumulative} = \eta_{pp} \times \eta_{trans} \times \eta_{electrol} \times \eta_{H_2comp} \times \eta_{fuelcell} \times \eta_{motor/wheels}$$

$$\eta_{cumulative} = 0.33 \times 0.96 \times 0.81 \times 0.90 \times 0.40 \times 0.92 = 0.085 = 8.5\%$$

All-electric car:

$$\eta_{cumulative} = \eta_{pp} \times \eta_{trans} \times \eta_{charger} \times \eta_{battery} \times \eta_{motor/wheels}$$

$$\eta_{cumulative} = 0.33 \times 0.96 \times 0.93 \times 0.93 \times 0.92 = 0.252 = 25.2\%$$

Table 5.1 tracks the cumulative efficiency through the different components. Given these assumptions, the all-electric car is three times more energy efficient than the fuel-cell car.

Direct conversion efficiency has limitations when we try to compare systems and sources that do not have the same starting and ending points. For example, it is straightforward to calculate the direct conversion efficiency for a diesel generator and a photovoltaic battery system:

- What is the direct conversion efficiency for a 10,000-watt diesel generator that consumes 1 gallon of diesel fuel per hour (138,000 Btu/gal)?

$$\eta = \frac{E_o}{E_d} = \frac{10{,}000 \text{ W}}{1 \text{ gal/hr} \times 138{,}000 \text{ Btu/gal} \times \frac{\text{Wh}}{3.412 \text{ Btu}}} = 0.25 = 25\%$$

- What is the direct conversion efficiency for a 100 m^2 silicon cell photovoltaic battery that produces 10,000 watts of electricity in full sun (1000 w/m^2)?

$$\eta = \frac{E_o}{E_d} = \frac{10{,}000 \text{ W}}{1000 \text{ W/m}^2 \times 100 \text{ m}^2} = 0.10 = 10\%$$

So, the diesel generator has 25% efficiency and the PV system has 10% efficiency. Does that tell the whole story? The two systems end at the same point but do not start the same. The diesel system needs a steady supply of nonrenewable fuel that takes energy to produce

table 5.1 Comparing Direct Conversion Efficiency for Fuel-Cell Vehicle and All-Electric Vehicle

System	Conversion	Component Efficiency	Fuel-Cell Car Cumulative Direct Conversion Efficiency	All-Electric Car Cumulative Direct Conversion Efficiency
Power plant	Fuel to kWh	33%	33.0%	33.0%
Transmission	kWh to kWh	96%	31.7%	31.7%
Electrolysis	kWh to H_2	81%	25.7%	—
H_2 compressor	H_2 to H_2	90%	23.1%	—
Fuel cell	H_2 to kWh	40%	9.2%	—
Charger	kWh to A-hr	93%	—	29.5%
Battery	A-hr to A-hr	93%	—	27.4%
Motor to wheels	kWh to ft-lb	92%	8.5%	25.2%

and get to the site. The PV system has no direct or continuous indirect energy requirements, but needs indirect one-time energy initially to manufacture the cells, modules, and batteries and transport and install them on site.

Other metrics consider indirect energy and differences in energy sources and systems.

5.2.2 Overall Energy Efficiency (η^*)

Overall energy efficiency takes into account both direct and indirect input energy.

Eq. 5.3
$$\text{Overall energy efficiency} = \eta^* = \frac{E_o}{E_d + E_i} \qquad 0 \le \eta^* \le 1$$

If the indirect input energy E_i includes one-time costs included in the manufacture and transport of conversion systems, those energy costs need to be spread over the life of the system.

Eq. 5.4
$$\eta^* = \frac{E_o}{E_d + E_{ic} + \dfrac{E_{iot}}{t_s}}$$

For example, the overall efficiency of our diesel generator would include the energy it takes to extract crude oil, refine it, and transport it to the generator. Let's say that indirect energy is 10% of the energy content of the resulting fuel. The resulting overall efficiency would be

$$\eta^* = \frac{E_o}{E_d + E_i} = \frac{10{,}000\text{ W}}{1.1 \times 1\text{ gal/hr} \times 138{,}000\text{ Btu/gal} \times \dfrac{\text{Wh}}{3.412\text{ Btu}}} = 0.227 = 22.7\%$$

Because η^* has the same numerator as η but a larger denominator, the fraction is smaller than η.

5.2.3 Life-Cycle Energy Efficiency (η_{lc}*)

Life-cycle analysis is useful because it consciously takes a long-term view of inputs and outputs. Life-cycle efficiency is essentially the same as η* but considers the output energy for the life of the system and all indirect input energy for the life of the system. Nuclear power systems, for example, have energy requirements for the fuel cycle (including waste management) and plant decommissioning that may be extensive and long-lasting, so their life-cycle costs include the following:

- The fuel cycle ($\mathbf{E}_{ic}$)
- Construction and materials ($\mathbf{E}_{iot}$)
- Operation/maintenance ($\mathbf{E}_{ic}$)
- Decommissioning ($\mathbf{E}_{iot}$)

Eq. 5.5 $$\textbf{Life-cycle energy output (lco)} = t_s E_o$$

where E_o = constant annual output, energy/year
t_s = system life, years

Eq. 5.6 $$\textbf{Life-cycle energy input (lci)} = t_s(E_d + E_{ic}) + E_{iot}$$

where E_d = constant annual direct inputs, energy/yr
E_{ic} = constant annual indirect inputs, energy/yr
E_{iot} = one-time indirect inputs, energy

Eq. 5.7 $$\textbf{Life-cycle efficiency} = \eta_{lc}^* = \frac{t_s E_o}{t_s(E_d + E_{ic}) + E_{iot}} = \frac{E_o}{E_d + E_{ic} + \frac{E_{iot}}{t_s}}$$

5.2.4 Energy Return on Energy Investment (EROI)

This measure ignores direct energy input and compares useful output energy to indirect input energy or the energy it takes to get energy. It indicates how much energy other than direct fuel energy input must be invested to get a unit of useful energy.

Eq. 5.8 $$\textbf{Energy return on energy investment} = \text{EROI} = \frac{E_o}{E_i}$$

Ideally, EROI is greater than one. If it is less than one, the system takes more indirect input energy to produce useful output energy and it may not be worth it, unless we can replace depletable oil and other carbon-emitting fossil energy with renewable energy in the process.

The analysis time period or product unit must be consistent in the numerator and denominator. If E_i includes only continuous inputs, E_o and E_i can be measured as energy per year or energy per unit product (such as gallon of equivalent fuel or kWh of electricity). If $\mathbf{E_i}$ is primarily a one-time input (such as for wind or PV systems) then life-cycle $\mathbf{E_o}$ and $\mathbf{E_i}$ should be used.

Eq. 5.9

$$EROI = \frac{t_s E_o}{E_{iot}}$$

when $\mathbf{E_i} = \mathbf{E_{iot}}$, and $\mathbf{E_o}$ in energy/year

This metric can illustrate the diminishing returns of our energy investment in energy production as we move toward depletion of conventional energy sources. It is taking more energy to make energy. In the early days of oil production, for example, reservoirs were easy to tap and indirect energy investments were low. As we have depleted these reservoirs, we have had to go deeper and farther to get oil and it has taken more energy to do that. The same has been true for coal and natural gas. According to a study by Cleveland et al. (2005), the EROI of U.S. oil production in the 1930s was 100 to 1. In 2000, it was 20 to 1. For new discoveries, it is 8 to 1. Coal production had an EROI of 100 in 1950; in 2000, it was about 80.

As we move toward unconventional fossil fuels, this becomes even more of an issue. Deep offshore oil deposits, heavy crude deposits, oil sands, and oil shale require more energy to extract and process, reducing EROI. One estimate of Canadian oil sands gives an EROI of 3. This is a double whammy for carbon emissions because more fossil fuel combustion is needed just to produce useful fuels so they can be burned.

EROI can also be used to assess the viability of new energy options on an energy return basis, such as biofuel ethanol, coal gasification, hydrogen fuel-cell systems, and others. Table 5.2 gives the results of several studies of EROI. The top five entries show the diminishing returns of the U.S. oil, gas, and coal production industries. Undocumented estimates of oil shale and oil sands EROI are 3 to 3.5. The next nine entries give EROI for several electricity generating options. Hydro has a high EROI of 205, and some renewable sources of electricity (wind [80], sawmill wastes [27], and photovoltaic [9]) fare better than coal with scrubbers (5) and natural gas combined cycle with 2000 km pipeline (5). Nuclear EROI is estimated at 16; EROI of solar photovoltaics is estimated at 7 to 14 depending on the technology.

Of course, all the results depend on the assumptions of indirect energy inputs that vary from one study to the next, so it is difficult to compare one result to another. This is dramatically clear in the current debate over biofuels. In a battle of scientific studies, academic and government researchers have calculated EROI for corn-based ethanol ranging from 0.78 to 1.29, and for switchgrass-based ethanol from 0.79 to 10.3. See Section 5.2.8 on energy analysis of ethanol.

5.2.5 Energy Payback Time (EPBT)

Energy Payback Time (EPBT) gives the time it takes an energy system to recover its one-time input energy with output energy. It divides one-time input energy by annual energy output. It is a particularly useful measure for renewable energy systems such as wind and photovoltaics, the costs of which are dominated by one-time development. For such systems, it is equivalent to 1/EROI.

table 5.2 **Energy Return on Energy Investment (EROI) for Various Energy Sources/Systems**

Source/System	EROI	Literature Source
U.S. oil and gas production, 1930	100	Cleveland (2005)
U.S. oil and gas production, 2000	20	Cleveland (2005)
U.S. gasoline production	7	Cleveland (2005)
U.S. coal production, 1950	100	Cleveland (2005)
U.S. coal production, 2000	80	Cleveland (2005)
Electricity from hydro with reservoir	205	Gagnon, et al. (2002)
Electricity from wind	80	Gagnon, et al. (2002)
Electricity from sawmill wastes	27	Gagnon, et al. (2002)
Electricity from nuclear	16	Gagnon, et al. (2002)
Electricity from PV modules	9	Gagnon, et al. (2002)
Electricity from coal (with SO_2 scrubbers)	5	Gagnon, et al. (2002)
Electricity from natural gas CC (2000 km del)	5	Gagnon, et al. (2002)
Electricity from biomass plantation	5	Gagnon, et al. (2002)
Electricity from fuel cell, H_2 from NG reform	2	Gagnon, et al. (2002)
PV modules (thin-film CIS)	14	Knapp and Jester (2001)
PV modules (crystalline silicon)	7	Knapp and Jester (2001)
U.S. ethanol fuel from corn	1.67	Shapouri, et al. (2004)
U.S. ethanol fuel from corn	0.78	Pimentel and Patzek (2005)
U.S. ethanol fuel from corn	1.29	Farrell, et al. (2006)
U.S. ethanol fuel from switchgrass	0.79	Pimentel and Patzek (2005)
U.S. ethanol fuel from switchgrass	10.3	Wang (2005)
U.S. ethanol fuel from switchgrass	8.3	Farrell, et al. (2006)
U.S. biodiesel from soybeans	3.20	U.S. DOE, USDA (1998)
U.S. biodiesel from soybeans	0.67	Pimentel and Patzek (2005)

Eq. 5.10

$$\text{Energy payback time} = \text{EPBT} = \frac{E_{iot}}{E_o}$$

Eq. 5.11

$$\text{For } E_i = E_{iot}\text{, EPBT} = \frac{1}{\text{EROI}}$$

A good example of EPBT is Knapp and Jester's (2001) study of photovoltaic modules. They estimated total indirect input energy for manufacturing and installing two types of PV modules:

- Crystalline silicon PV modules: $\mathbf{E_i = E_{iot} = 5600\ kWh/kW_p}$ (kilowatt-hour electric input per kilowatt peak power output of module)
- Thin-film copper indium diselenide (CIS) modules: $\mathbf{E_i = E_{iot} = 3100\ kWh/kW_p}$

The kW_p of the module occurs at peak sun (1 kW/m^2). A typical average value for solar energy falling on a site in the United States is 1700 kWh/m^2/year. That means that each kW_p will produce 1700 kWh per year on average for the United States. System losses due to wires, inverters, operating temperatures, and so on, were accounted for by a performance ratio (PR) of 0.8. The study calculated EPBT for the two types of PV modules.

Given these values, the EPBT calculations are easy. Without the performance ratio considered,

$$\text{EPBT (silicon)} = \frac{E_{iot}}{E_o} = \frac{5600\ \text{kWh/kW}_p}{1700\ \text{kWh/kW}_p} = 3.3\ \text{years}$$

$$\text{EPBT (thin-film CIS)} = \frac{E_{iot}}{E_o} = \frac{3100\ \text{kWh/kW}_p}{1700\ \text{kWh/kW}_p} = 1.8\ \text{years}$$

To consider the performance ratio (PR), E_o is multiplied by PR or EPBT is divided by PR:

$$\text{EPBT w/PR (silicon)} = \frac{\text{EPBT}}{\text{PR}} = \frac{3.3\ \text{years}}{0.8} = 4.1\ \text{years}$$

$$\text{EPBT w/PR (thin-film CIS)} = \frac{\text{EPBT}}{\text{PR}} = \frac{1.8\ \text{years}}{0.8} = 2.2\ \text{years}$$

If the expected life of these modules is 30 years, both PV modules have an energy payback period well within their lifetime.

We can then calculate the EROI for these modules, assuming the PR of 0.8:

$$\text{EROI} = \frac{E_o}{E_i} = \frac{t_s E_o}{E_{iot}} = \frac{t_s}{\text{EPBT}}$$

$$\text{EROI (silicon)} = \frac{30\ \text{years}}{4.1\ \text{years}} = 7$$

$$\text{EROI (thin-film CIS)} = \frac{30\ \text{years}}{2.2\ \text{years}} = 14$$

These are the EROI values that appear in Table 5.2.

5.2.6 Net Energy Value (NEV) or Energy Balance

Net energy value (NEV) is similar to EROI, but it uses the difference rather than the ratio to compare useful output energy to input energy.

Eq. 5.12 $$\text{Net energy value} = \text{NEV} = E_o - E_i$$

Because this is an absolute value rather than a dimensionless ratio, it is computed as energy per unit of energy or fuel, such as Btu/gal. Farrell, et al. (2006), argue that the NEV metric is more robust than EROI, especially when there is question about how to treat co-product energy, or the energy content of feed and fuel outputs other than the primary product. For example, production of ethanol not only produces ethanol liquid fuel, but also co-product feed and solid fuel that have energy value. The EROI value depends significantly on whether the co-product energy is treated as a negative input (in the denominator of the ratio) or a positive output (in the numerator). With NEV it doesn't matter.

NEV and EROI calculations vary depending on differing assumptions of indirect input and output energy and EROI depends on treatment of co-product energy. These assumptions can be quite contentious, as we see in the continuing debate about the net energy of corn-based ethanol (see Section 5.2.8).

5.2.7 Fossil Fuel Ratio (FFR) and Petroleum Input Ratio (PIR)

Like EROI, fossil fuel ratio (FFR) is the ratio of energy output to energy input, but it includes both direct and indirect fossil fuel input energy. Petroleum input ratio (PIR) is similar but it focuses on direct and indirect petroleum input and inverts the ratio to energy input to output. These are useful measures because they reflect relative dependency of petroleum or fossil fuels (see Figures 5.3 and 5.4).

Eq. 5.13

$$\textbf{Fossil fuel ratio} = \textbf{FFR} = \frac{E_o}{(E_d + E_i)_{FF}}$$

where $(E_d + E_i)_{FF}$ = direct + indirect fossil fuel energy input

Eq. 5.14

$$\textbf{Petroleum input ratio} = \textbf{PIR} = \frac{(E_d + E_i)_{Petro}}{E_o}$$

where $(E_d + E_i)_{Petro}$ = direct + indirect petroleum energy input

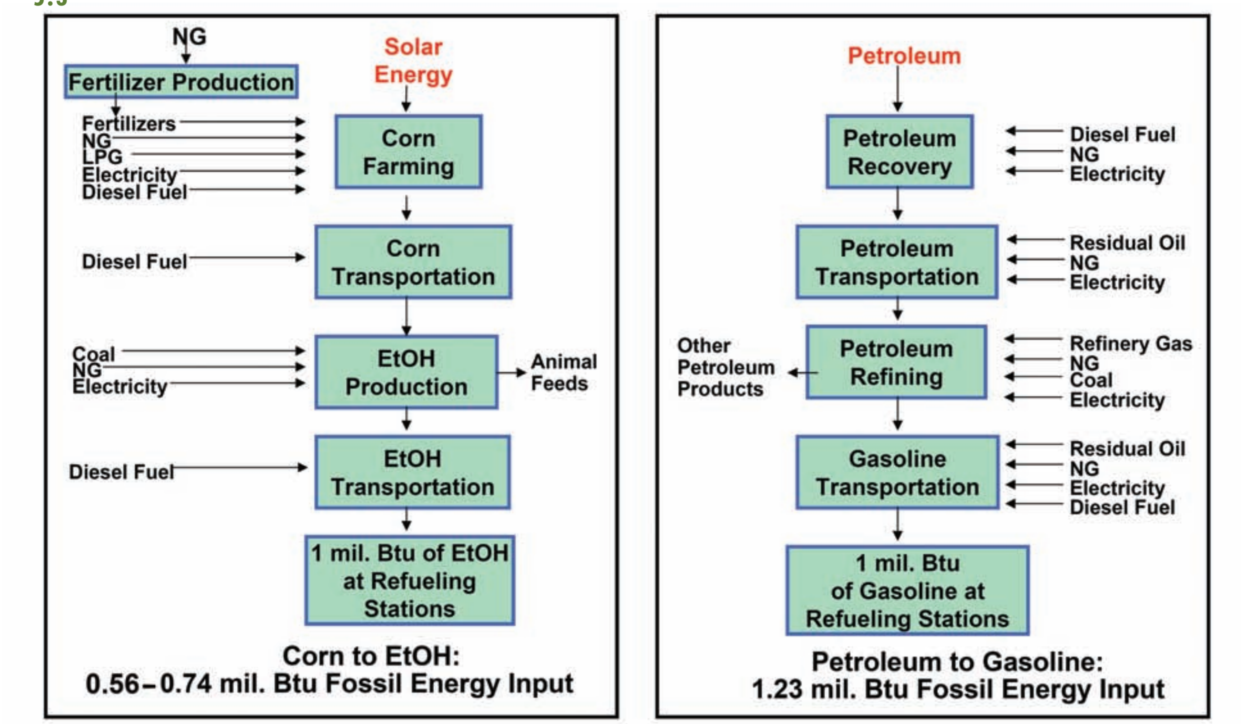
Michael Wang from Argonne National Lab argues that FFR and PIR are better measures than EROI in addressing our national objectives to reduce oil use and the greenhouse gas emissions from combustion of fossil fuels. Although gasoline has a better EROI (8) than corn ethanol (1.2 to 1.7), gasoline's FFR includes the petroleum fuel energy and the FFR ratio is 0.81, while ethanol's FFR is 1.79. Figure 5.3 illustrates Wang's analysis of the fossil energy to produce 1.0 million Btu of fuel: it takes 0.56–0.74 million Btu of fossil fuels for corn ethanol (depending on energy credit for co-products) and twice that, or 1.23 million Btu of fossil fuels, for gasoline.

5.2.8 Applying Energy Analysis to Biofuel Ethanol

The 2005 and 2007 Energy Policy Act, provide significant incentives for the production of biofuel ethanol. Compared to 2004, oil companies are mandated to double their use of ethanol in transportation fuels by 2012 and increase it by ten times by 2022. Is this a good idea?

Well, it depends on whom you talk to. And that makes ethanol a good example of the importance of assumptions made in energy analysis studies. David Pimentel from Cornell has long argued that ethanol fuel from corn is an energy loser (i.e., it takes more energy to produce it that it would replace). On the other hand, Hosein Shapouri from USDA and others have come up with different results showing ethanol to have an EROI greater than one and

figure 5.3 Fossil Fuels Needed to Produce One Million Btu of Fuel Ethanol and Gasoline



Corn to ethanol (EtOH) takes 0.56–0.74 million Btu (range depends on energy credits for co-products): FFR = 1/0.56 = 1.79. Petroleum to gasoline takes 1.23 million Btu: FFR = 1/1.23 = 0.81.

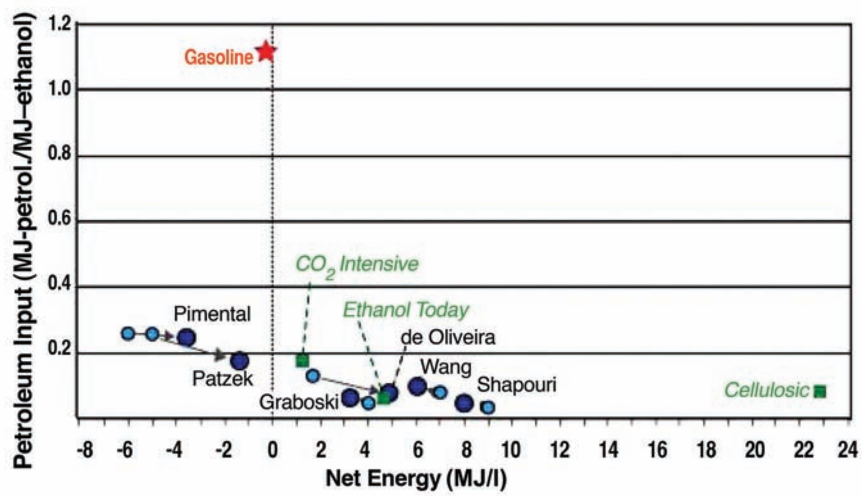
NG = natural gas; LPG = liquid petroleum gas
Source: Wang, 2005

a positive NEV. Why the difference? Ethanol advocates argue Pimentel uses outdated corn production and ethanol processing data, discounts co-product energy, and wrongly takes the analysis back too far (e.g., to indirect energy required in manufacturing the farm equipment needed to grow the corn). Pimentel argues that Shapouri and others omit some of the energy inputs in the ethanol production process. Who is right?

Farrell, et al. (2006), at the Energy and Resources Group (ERG), University of Calfornia-Berkeley, tried to bring some order to this debate by adjusting various studies with common assumptions. They also conducted their own analysis using their ERG Biofuel Analysis Meta-Model (EBAMM). The comparison of net energy and petroleum input ratio (Figure 5.4) shows positive net energy with the exception of Pimentel and Patzek. PIR values also vary, but all are 80% to 95% better than gasoline. The Berkeley group's assessment of cellulosic ethanol has significantly higher net energy than all of the studies of corn-based ethanol.

Calculating net energy and EROI for ethanol. Some calculations for corn- and cellulose-based ethanol can illustrate the process of net energy analysis and the importance of calculated or assumed values of energy inputs and outputs to the results. In addition, we can

figure 5.4 **Net Energy and Petroleum Input for Fuel Ethanol and Gasoline**



Farrell et al. (2006) plot PIR and NEV results from various studies of corn feedstock ethanol, adjusted to common assumptions (arrows to large dots), as well as gasoline and their own EBAMM cases—cellulosic ethanol, ethanol today, and CO_2-intensive ethanol. All ethanol cases show considerable petroleum savings over gasoline. Cellulosic ethanol has much higher net energy than corn ethanol.

Source: Farrell, et al., SCIENCE 311:506–508 (2006). Reprinted with permission from AAAS.

also see that EROI ratio depends on whether co-product energy is treated as negative input or positive output, especially when it is large compared to input energy as it is in the Farrell et al. cellulose case. Table 5.3 gives the values of the input, output, and co-product energy estimated in three well-cited studies. We then step through calculations of net energy (NEV) and EROI. We use Btu/gallon of ethanol, but then convert to megajoules per liter (MJ/l) (1 Btu/gal = 2.79×10^{-4} MJ/l) to be consistent with the values in Figure 5.4.

We employ our Equations 5.12 and 5.8:

$$\text{NEV} = E_o - E_i$$

$$\text{EROI} = \frac{E_o}{E_i}$$

Pimentel and Patzek (2005) estimate higher input energy and no credit for co-product energy:

$$\text{NEV} = 77{,}053 \text{ Btu/gal} - 99{,}096 \text{ Btu/gal} + 0 \text{ co-product} = -22{,}043 \text{ Btu/gal} = -6.1 \text{ MJ/l}$$

$$\text{EROI} = \frac{77{,}053 \text{ Btu/gal}}{99{,}096 \text{ Btu/gal}} = 0.78$$

Shapouri, et al. (2004), estimate lower input energy and a significant credit for co-product energy:

table 5.3 Contradictory Studies on NEV and EROI for Fuel Ethanol from Corn

Study	E_o, Output Ethanol Energy, Btu/gal	E_i, Input Energy, Btu/gal	Co-Product Energy, Btu/gal	$E_o - E_i$, Net Energy Value (NEV), Btu/gal	$\frac{E_o}{E_i}$ = EROI
Shapouri, et al. (2004)	76,330	71,800	26,000	30,528	1.67/1.43
Pimentel and Patzek (2005)	77,053	99,096	0	–22,043	0.78
Farrell, et al. (2006), corn	76,060	74,265	14,700	10,505	1.29/1.22
Farrell, et al. (2006), cellulose	76,060	11,120	17,200	82,140	8.3

$$\text{NEV} = 76{,}330 \text{ Btu/gal} - 71{,}800 \text{ Btu/gal} + 26{,}000 \text{ co-product} = 30{,}528 \text{ Btu/gal} = 8.5 \text{ MJ/l}$$

$$\text{EROI} = \frac{76{,}330}{71{,}700 - 26{,}000} = 1.67 \text{ (if co-product treated as negative input)}$$

$$\text{EROI} = \frac{76{,}330 + 26{,}000}{71{,}700} = 1.43 \text{ (if co-product treated as positive output)}$$

Farrell, et al. (2006), estimate slightly higher input and lower co-product than Shapouri:

$$\text{NEV} = 76{,}060 - 74{,}265 + 14{,}700 = 16{,}495 \text{ Btu/gal} = 4.6 \text{ MJ/l}$$

$$\text{EROI} = \frac{76{,}060}{74{,}265 - 14{,}700} = 1.29 \text{ (if co-product treated as negative input)}$$

$$\text{EROI} = \frac{76{,}060 + 14{,}700}{74{,}265} = 1.22 \text{ (if co-product treated as positive output)}$$

Farrell, et al., also estimate inputs and co-products for cellulosic ethanol:

$$\text{NEV} = 76{,}060 - 11{,}120 + 17{,}200 = 82{,}140 \text{ Btu/gal} = 22.9 \text{ MJ/l}$$

$$\text{EROI} = \frac{76{,}060}{11{,}120 - 17{,}200} = -12.5 \text{ (meaningless) (if co-product treated as negative input)}$$

$$\text{EROI} = \frac{76{,}060 + 17{,}200}{11{,}120} = 8.3 \text{ (if co-product treated as positive output)}$$

5.2.9 Accounting for Energy Quality in Net Energy Analysis

Net energy analysis and other metrics estimate direct and indirect input energy needed to produce useful energy. This input energy can vary from raw fuel to electricity. Does the type of input energy matter? Are all joules created equal? The second law of thermodynamics says that they are not. Higher quality, lower entropy energy is more precious than lower quality thermal energy. If, for example, an energy source or system requires input energy of high-quality electrical joules, whereas another requires an equal amount of input energy joules as low-quality heat, the first will be harder to come by. So we might try to account for that in our energy analysis.

This is easier said than done. Analysts have developed approaches to aggregate input energy by quality using *emergy* and *exergy* as measures of quality. Emergy analysis was first developed by Howard Odum. The standard units of emergy are solar emjoules (SEJ) or the solar energy needed to produce another type of energy. For example, each heat unit of electricity (1 joule) is 1.59×10^5 SEJ, which is derived from the sunlight required to produce 1 joule of standing wood (3.23×10^4 SEJ) as well as losses incurred in the harvesting, transport, and steam cycle to convert the wood to electricity.

Exergy embraces the second law and is defined as the potential for mechanical work that can be extracted from a type or flow of energy. For example, the exergy of a fuel or heat source is calculated by multiplying its heat equivalent by the Carnot factor $(1 - T_a/T_o)$, where T_a is ambient temperature and T_o is output temperature, both in kelvin (see Chapter 10 for discussion of Carnot efficiency). High-quality mechanical and electrical energy are not constrained by this factor because they can be transformed directly to useful work. Using exergy analysis, input energy can be differentiated by quality. Similar to emergy, however, exergy has conceptual appeal, but limited practical value.

A third approach used to incorporate energy quality in energy analysis uses energy prices as a proxy for energy quality. Energy prices reflect value and value reflects quality. On a per-energy-unit basis, electricity has a higher price than natural gas, natural gas has a higher price than petroleum products, and petroleum products have a higher price than coal. Using price as an indicator for quality, the EROI equation can be rewritten as a "quality corrected EROI" or the ratio of the sum of individual energy outputs and inputs each multiplied by a quality factor based on energy price.

These heroic efforts to be true to the second law and incorporate energy quality in energy analysis are valiant, but we should first try to find common ground on basic assumptions on energy inputs in simple net energy assessments before complicating the analysis with energy quality considerations.

5.3 Energy Monitoring and Energy Audits

We wish to use the results of energy analysis to make smart energy choices, to design and manage energy systems, and to use energy more efficiently. Energy analysis requires good information and the best data come from physical monitoring of systems, of energy consumption, and of functions performed.

Energy monitoring can be as simple as reviewing your monthly electric utility bill or jotting down your car's odometer reading when filling up with gas so you can compute miles per gallon. It can be as complicated as installing a multifunction computer datalogger that retrieves data on energy use and ambient conditions and sends the results to a distant receiving location via wireless technology. Whatever means are used, the point to remember is this: the better the data, the better are the analysis and results, and the better informed are the decisions that follow.

Energy monitoring is an important component of an **energy audit,** an analytical approach to assess energy consumption and identify potential efficiency improvements.

Before reviewing some basic energy monitoring methods, we need to introduce energy audits.

5.3.1 Energy Audits

Energy audits apply energy analysis methods to evaluate patterns and trends of energy consumption and efficiency opportunities in households, government agencies, and private commercial and industrial firms. Auditing is applied mostly to buildings (see Chapter 6) but also to transportation fleets and industrial processes. It is an important first step in energy management services. Although we will discuss methods used in energy auditing in later chapters, a brief introduction is useful here.

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), which sets standards for building energy systems and audits, there are three levels of energy audits:

> Level 1: Walk-through or visual assessment—Rapid assessment looks for energy problems and solutions that are easily identified and helps scope out needed monitoring and analysis.
>
> Level 2: Energy survey and analysis—This standard audit includes monitoring of historical utility billing data, submeter data, and use of monitoring and diagnostic equipment where necessary. The standard audit will identify potential energy conservation measures (ECMs) and often calculate their cost-effectiveness.
>
> Level 3: Detailed analysis of capital intensive modifications—This extensive audit goes beyond basic analysis and may employ computer simulations, more detailed monitoring, and more sophisticated economic assessment of major modifications to the building or industrial process.

A basic procedure for Level 1 and 2 audits includes the following steps:

1. Perform preliminary walk-through to identify audit goals and objectives.
2. Analyze billing data from energy suppliers to determine energy consumption trends.
3. Use submetered data as available.
4. Review specifications, mechanical drawings, and other information on energy systems and equipment, building envelope, lighting, and so on, to assess opportunities for efficiency improvements.
5. Perform facility walk-through and diagnostics, including interviews with users and use of diagnostic devices such as lighting monitors, blower door (for air leakage), and so on.
6. Monitor energy systems and equipment using submetering devices and data loggers.
7. Synthesize results and findings.
8. Identify potential ECMs, conduct economic analysis of options, and prepare final report with recommendations.

We discuss step 2 using billing data and step 6 on monitoring below, step 8 on economic analysis in the next section, and other auditing methods for buildings in Chapters 6–8.

5.3.2 Monitoring with Energy Billing Information

Energy utilities and companies that provide fuel and electricity monitor energy sales for billing purposes. Electric and natural gas utilities have cumulative kWh and gas meters on our houses that they read monthly to determine our consumption and to bill us accordingly; fuel oil distributors fill our tanks, using a flow meter to measure their sale in gallons; gas stations also use flow meters to measure the gallons we buy at the pump. We can use this monitored energy sale information to calculate consumption and efficiency of use. Solution Box 5.1 gives my first assessment of fuel economy of my Toyota Prius.

In our homes, our utility bills are our best source of energy monitoring data, and as discussed in the last section, one of the first data sources in energy audits. These bills give us a monthly record of consumption of electricity (kWh) and natural gas (therms = 100,000 Btu, or about 100 cubic feet [ccf]). We can plot the results to see variation from month to month, from heating to cooling season, from year to year. We can see changes resulting from new appliances or from energy conservation measures.

Some more sophisticated methods have been developed to track and analyze utility bill data. For example, PRISM, an analytical computer software developed at Princeton, uses data from weather records and utility bills to assess historical heating and cooling energy use. This method has been useful in evaluating efficiency intervention, such as weatherization retrofit, when other monitoring methods are not used. Because the billing data on energy consumption are stored with the utility, they can be accessed at any time. Samples of energy data before and after the intervention can be corrected for weather variation and compared to see what savings were achieved by the weatherization.

Several energy service vendors market utility bill data tracking software and online services to help companies and institutions manage their energy use. Examples include UtiliVision's Energy Watchdog (http//www.energywatchdog.com) and Abraxas Energy Consulting's Metrix Utility Accounting System (http://www.abraxasenergy.com/metrix.php).

5.3.3 Energy Data Logging

Data logging involves the use of meters and loggers to measure energy use and functions performed for energy analysis and evaluation studies. The most commonly used meters are the same ones used by utilities for billing purposes, such as the kWh (Figure 5.5) and gas meters on a building or housing unit. We may want more detailed or site-specific data than these meters provide, so we submeter smaller units or individual equipment or appliances to get this detail. Some meters measure electricity consumption, but others measure the time that electricity is flowing. These latter **"run-time" meters** simply measure the cumulative

SOLUTION

SOLUTION BOX 5.1

Using Gasoline Receipts to Monitor Vehicle Fuel Economy

I bought a Toyota Prius in 2005 and wanted to know its fuel economy compared to the EPA ratings.

Solution:

I kept my gasoline receipts for the first four tankfuls in my Prius and recorded on each the odometer mileage when I filled it up. I bought the car with only 5 miles on the odometer, and the dealer filled it up at that time. I logged the date, gallons, and mileage in the following table, then calculated the miles per gallon (mpg) efficiency for each tankful and cumulative.

$$\textbf{mpg} = \frac{\textbf{miles per tank}}{\textbf{gallons per tank fill-up}}$$

The miles per tank is the odometer reading minus the odometer reading at last fill-up.

For the first tankful: Tankful #1: $\textbf{mpg} = \dfrac{(410 - 5)}{8.5} = \textbf{47.6 mpg}$

The cumulative mpg = total miles/total gallons = $\dfrac{(1698 - 5)}{36.4} = \textbf{46.5 mpg}$

Date	Miles	Fill-Up Gallons	Miles/Tankful	Miles per Gallon
4/30	5	??	NA	NA
5/20	410	8.5	405	47.6
6/15	833	8.9	423	47.5
7/7	1255	9.2	422	45.9
8/1	1698	9.8	443	45.2
Total		36.4	1693	46.5

How do I interpret these results? The mpg is less than the EPA estimate for the Prius (60 city, 51 highway), but I've heard this is typical for most cars. The mpg decreased since my first tankful. I began to monitor the type of driving that dominated each tankful, such as highway, city, short trips, long trips, as well as tire pressure and the way I drive. By using my monitoring results, I began to fine-tune my driving to improve efficiency. Two years later I am getting 50+ mpg on an average tankful.

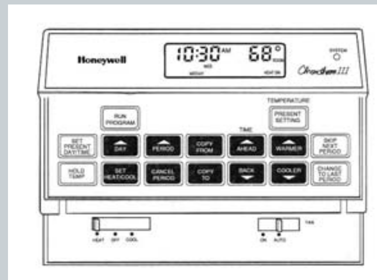
time the equipment is on. They are useful for thermostatically controlled devices such as oil and gas furnaces and refrigerators. For oil and gas furnaces, if we know the run-time and the furnace firing rate (fuel volume per minute), we can calculate fuel use. Sidebar 5.1 describes several submeters on the market.

SIDEBAR 5.1

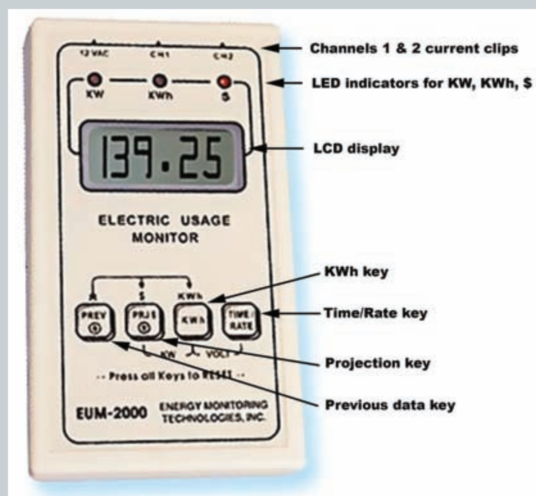
Examples of Submeters for Energy Monitoring

A. **Honeywell Programmable Digital Thermostat** not only allows you to program temperature settings by time but also logs run-time of the furnace or heat pump and thus can be used for monitoring energy.

B. **Kill-a-Watt submeter** is simply plugged into the outlet, and it measures power draw (W), energy used (Wh), and run-time of device plugged into it.



C. **Electric Usage Monitor** is a submeter with current clips that can be clipped to any circuit and measure power (kW), energy (kWh), and run-time. It can also be programmed with electrical rates to read off dollars instead of energy and can be used to project energy use over a long period of time.



Dataloggers are electronic devices that store digital data retrieved from different sensors. These sensors can measure temperature, pressure, light, run-time, weather conditions, and energy parameters. The data can be easily downloaded to a computer and converted to spreadsheet form. Some loggers are equipped with modems or telemetry systems where phone

SIDEBAR 5.2

Examples of Dataloggers for Energy Monitoring

A. The **HOBO series** of dataloggers by Onset are the size of a matchbox and they can be programmed to collect various data at desired time intervals. Built-in or remote plug-in sensors can be used. After monitoring, the HOBO can be plugged into a computer USB port to download data to spreadsheet software.

B. **DataTaker datalogger** is a conventional datalogger with multiple ports for various data sensors. Retrieved data can be downloaded to a computer.

C. Onset's **Solar Stream wireless data transceiver** can monitor energy use, weather, and other data at remote locations. The data are transmitted via wireless technology and downloaded automatically to a receiver or receiving computer. The battery for the datalogger and transceiver is trickle charged by a small PV array.

lines are not available so that data can be retrieved remotely. Sidebar 5.2 illustrates some of the dataloggers used for energy analysis. The simplest is the HOBO datalogger, which is the size of matchbox. The HOBO can be programmed to collect various data, placed at a location to collect the data, and then plugged into a computer USB port to download the data.

5.4 Economic Analysis of Energy Systems

We have been talking about various means of measuring energy consumption and efficiency. For many reasons we want to minimize energy use and maximize efficiency and the functions

figure 5.5 **Kilowatt-hour Meter for Utility Billing**

This meter is also a useful monitor for energy analysis. Although the dials read cumulative kWh used, the meter can be used to measure power draw. The wheel rotates at a watt-hour per revolution equal to the Kh factor given on the face of the meter. If you turn on only those devices you wish to measure and count the revolutions per minute (rpm), you can calculate the power drawn by the device(s) power draw by multiplying the rpm by the Kh factor and 60 sec/min to get the kilowatts: **Power (kW) = Rev/min × Kh Wh/Rev × 60 min/h = kW.**

energy provides for us. We want to accelerate our use of clean, renewable energy sources, and reduce the pollution and other impacts of conventional energy. Some people will turn to sustainable energy not because it will save them a lot of money but because they think it is good for the future of the planet or is just fun to do.

However, if we want everyone to turn to sustainable energy, we better make sure it is worth it financially. We as individuals, communities, and society have limited economic resources, and we need to invest them wisely or we will have little left for other needs of life. Although economic analysis does not capture all of the values we have as individuals and society, it is a necessary first step to see if certain options are worth doing.

In this section we take our energy assessment methods a step further to include economic analysis. Remember, though, it all starts with energy analysis. We need to quantify energy use and efficiency first. We can then put economic value on those energy numbers based on energy rates and prices, and then proceed to calculate cost-effectiveness and economic feasibility.

Before discussing those measures of cost-effectiveness, it is important to introduce monetary value of energy as well as life-cycle costing and the time-value of money.

5.4.1 Economic Value of Energy

Before going too far into economic analysis, we need to talk about putting energy into monetary terms. This is pretty easy because energy is bought and sold in the marketplace. Energy prices are set by the market as influenced by government policy. For example, fuel oil is primarily market-based, gasoline is market-based with federal and state taxes (more of a fee because they are used largely for road building and maintenance), and retail natural gas and electricity are regulated markets (because customers are largely captured by their providing utilities). Government subsidies, taxes, and environmental policies have a range of effects on the prices of different energy sources. We will talk more about the effect of policy on energy prices later.

Energy prices have been volatile and increasing. Table 5.4 gives nominal prices for selected fuels and electricity for 1998 to 2007 in price per unit and commensurate price per million Btu. In those nine years, gasoline prices increased an average 10% per year, natural gas 6.5% per year, and electricity 2.6% per year. Gasoline prices have more than doubled since 2002. Higher-quality electricity costs much more per unit of energy than natural gas or fuel oil but that gap has closed a bit in the last few years. Higher natural gas prices are affecting the cost of natural gas–fired electricity.

Figure 5.6 shows the national average retail and wholesale price of gasoline and crude oil for August 2006 to August 2007. Prices turned up in late 2007 when oil approached $100 per barrel or $2.38 per gallon. Other trends of energy prices are available from U.S. EIA's energy price reports (http://www.eia.doe.gov); click on energy type and then on retail prices to find EIA's full database.

We use these energy prices to translate energy consumption into economic costs. Solution Box 5.2 gives an example showing that translating heating energy to economic cost depends on the fuel type.

Of course, these costs may be more next year if prices keep going up. If we want to plan ahead or predict future costs, we have to consider how prices will change in the future, and for this and other reasons time becomes an important factor in energy and economic analysis.

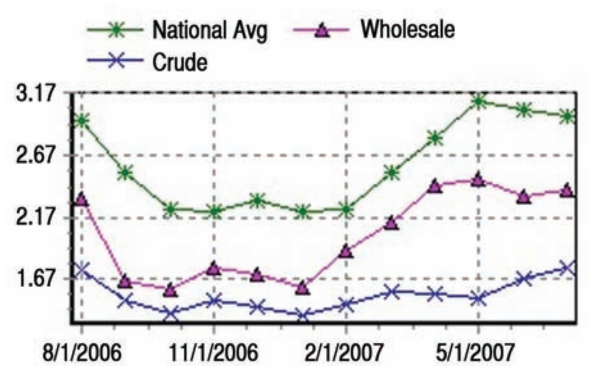
table 5.4 **Energy Prices for Selected Sources, 1998–2007**

	Gasoline	Natural Gas	Electricity	Gasoline	Natural Gas	Electricity
	all grades	residential	residential	all grades	residential	residential
Year	$ per gal	$/ccf (100 ft^3)	¢ per kWh	$/10^6 Btu	$/10^6 Btu	$/10^6 Btu
1998	1.07	6.82	8.26	8.56	6.61	24.21
1999	1.18	6.69	8.16	9.44	6.49	23.92
2000	1.52	7.76	8.24	12.16	7.53	24.15
2001	1.46	9.63	8.58	11.68	9.34	25.15
2002	1.37	7.89	8.44	10.96	7.65	24.74
2003	1.60	9.63	8.72	12.80	9.34	25.56
2004	1.90	10.75	8.95	15.20	10.43	26.23
2005	2.31	12.84	9.45	18.48	12.45	27.70
2006	2.62	13.75	10.40	20.96	13.35	30.48
2007	2.80*	14.10**	10.62***	22.40	13.68	31.13

* through October: **through August ***through July

Source: U.S. EIA, 2007

figure 5.6 **Retail and Wholesale Gasoline and Crude Oil Prices, August 2006—August 2007**



SOURCE: AAA Fuel Gauge Report, 2007, www.aaa.org

5.4.2 Life-Cycle Costing and Time-Value of Money

5.4.2.1 Life Life-Cycle Costing

We introduced life-cycle thinking in Section 5.1 and life-cycle energy requirements in Section 5.2.4. If we are to understand the full energy requirements of a system, we need to look down the road and consider longer-term commitments. For example, for a large commitment to nuclear power, we have to consider the future energy needs and monetary costs of not only plant construction and operation and fuel mining and enrichment but also plant decommissioning and disposal of wastes that may last longer than our human history to-date. In August 2005, in response to a 2004 court case, the EPA proposed radiation exposure standards for the Yucca Mountain nuclear waste site that would protect people in the area for one million years! Once approved, the standards would allow DOE to file an application to construct and operate the site, the next step forward for the $58 billion facility. Planning for one million years has presented new challenges to the agency's energy and economic analysts.

The same life-cycle cost issue is even more germane to mundane personal decisions such as buying lightbulbs. We are all tempted to choose energy-consuming items that are initially cheaper, when in fact they will be far more expensive over the life cycle of the product. Solution Box 5.3 illustrates the simple calculations for life-cycle cost of incandescent lightbulbs and compact fluorescent lamps. This exercise is not complete without considering the full costs of manufacturing and disposal of the bulbs, but we assume that they are the same for the two cases.

5.4.2.2 Time-Value of Money

Economic analysis recognizes that money has a time dimension. If we borrow money, we will have to pay back more than we borrow due to interest charges. If we invest our precious cash, we should consider the risk-free return we could get from simply putting it in a savings account. As a result, a dollar tomorrow is considered less valuable than a dollar today. We

SOLUTION

SOLUTION BOX 5.2

Translating Energy Consumption to Economic Cost

I estimate that it takes the same amount of energy (40 million Btu per year) to heat my house and my neighbor's house (we'll discuss how to calculate this in Chapter 6). She has baseboard electric heat and I heat with natural gas. Her baseboard electric operates at 100% efficiency (all the electricity ends up as heat in the house), whereas my natural gas furnace and forced-air system operates at about 80% efficiency (20% is lost in exhaust gases and losses in the duct system). If I pay \$1.30 per therm (1 therm = 100,000 Btu) for natural gas and she pays 10.5¢/kWh for electricity, how much does each of us pay per year for heating?

Solution:

My House:

$$\eta = \text{useful heating energy/natural gas (NG) energy input}$$

or

$$\text{NG energy input} = \frac{\text{useful heating energy}}{\eta}$$

$$= \frac{40 \times 10^6 \text{ Btu/yr}}{0.80}$$

$$= 50 \times 10^6 \text{ Btu/yr}$$

$$\text{NG cost} = \frac{\text{NG input Btu} \times \text{cost}}{\text{NG Btu}}$$

$$= 50 \times 10^6 \text{ Btu/yr} \times \frac{\$1.30}{10^5 \text{ Btu}} = \$650$$

My Neighbor's House:

$$\text{Electricity cost} = 40 \times 10^6 \text{ Btu/yr} \times \frac{\$0.105}{\text{kWh}} \times \frac{\text{kWh}}{3412 \text{ Btu}} = \$1231$$

"discount" future dollars to "present value" by a "discount rate" using the classic present value equation:

Eq. 5.15

$$P = \frac{F}{(1 + d)^n}$$

SOLUTION BOX 5.3

SOLUTION

Life-Cycle Economic Cost of Lightbulbs

When I need lightbulbs, I face a choice between bulbs that produce the same amount of light or lumens, one for $0.30 each, the other for $2.50 each. Which do I choose?

Solution:

My "buy-it-cheap" self tells me to grab the $0.30 bulbs, but my smarter "buy-it-least-cost" self makes me pause and after some thought (and a quick run of the numbers), the opposite answer emerges. The $0.30 incandescent bulb will ultimately cost much more than the $2.50 compact fluorescent lamp (CFL) over the life cycle, considering electricity and replacement costs.

What are the life-cycle costs of these two lightbulb alternatives: a $0.30, 60 W incandescent bulb with 1000-hour life or a $2.50, 11 W CFL with 10,000-hour life? Both produce the same lumens of light. We can assume a low electricity rate of $0.07/kWh and set a common time period for comparable analysis at 10,000 hours.

Incandescent Lightbulb:

1. Bulb cost: **$0.30/bulb × 1 bulb/1000 hr × 10,000 hr = $3.00** (10 bulbs needed for 10,000 hr)
2. Energy cost: **60 W × 10,000 hr × kWh/1000 Wh × $0.07/kWh = $42**
3. Life-cycle cost = $45 (ignoring labor cost to change the bulb 9 times)

Compact Fluorescent Lamp (CFL):

1. Lamp cost: **$2.50/lamp × 1 bulb/10,000 hr × 10,000 hr = $2.50** (1 lamp needed for 10,000 hr)
2. Energy cost: **11 W × 10,000 hr × kWh/1000 Wh × $0.07/kWh = $7.70**
3. Life-cycle cost = $10.20

Life-cycle cost savings of CFL over incandescent bulb: **$45.00 – $10.20 = $34.80**

The "cheap" incandescent bulb cost $4\frac{1}{2}$ times or $35 more than the "expensive" compact fluorescent lamp.

where P = present value dollars
F = future value dollars at year n
d = discount rate

This is the inverse of the compound interest equation that calculates the growth of dollars if invested at an annual interest rate:

Eq. 5.16
$$F = P(1 + i)^n$$

where P = present dollars
F = future dollars at year n
i = interest rate

If I have $100 and put it in a certificate of deposit (CD) with a 4% annual interest rate of return, what will the CD be worth in 10 years? Interest compounded annually increases each year's balance by 4% by the end of the year. The table steps this growth forward for each year:

Today	End of Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
$100	$104	$108.16	$112.48	$116.99	$121.67	$126.53	$131.59	$136.86	$142.33	$148.02

Alternatively, the compound growth equation can be used to calculate future value:

$$F = P(1 + i)^n = \$100(1 + 0.04)^{10} = \$148.02$$

If I expect to get a payment of $100 in 10 years, what is the present value assuming a discount rate of 4%?

$$P = \frac{F}{(1 + d)^n} = \frac{\$100}{(1 + 0.04)^{10}} = \$67.56$$

The time-value of money is important to consider for energy analysis that involves long time periods and high discount rates. For short time periods and for low discount rates, ignoring the time-value of money is usually not a problem. The following examples illustrate this guideline.

What is the present value of future $100 ten years (long) from now if the discount rate is 0.5% (low)?

$$P = \frac{F}{(1 + d)^n} = \frac{\$100}{(1 + 0.01)^{10}} = \$95.13$$

What is the present value of future $100 six months (short) from now if the discount rate is 10% (high)?

$$P = \frac{F}{(1 + d)^n} = \frac{\$100}{(1 + 0.10)^{0.5}} = \$95.31$$

What is the present value of future $100 ten years (long) from now if the discount rate is 10% (high)?

$$P = \frac{F}{(1 + d)^n} = \frac{\$100}{(1 + 0.10)^{10}} = \$38.55$$

In each case, ignoring the discount rate and setting $P = F$ for the low d and/or short n would give only a small (5%) error, but ignoring it for high d and long **n** would give a large (62%) error.

How do we choose a discount rate? Many factors contribute to an appropriate discount rate: prevailing interest rates (and those in the future), rates of overall inflation, inflation or deflation of fuel and electricity prices, expected returns from alternative investments, and so on. All these factors are uncertain so a bit of guesswork is included. Given the uncertainties, a simple approach is appropriate. The major factors are interest rate and fuel price inflation.

Eq. 5.17 $$d = i - r$$

where d = discount rate
i = interest rate
r = inflation rate for energy prices

Interest rate (i) may depend on the situation. If money is borrowed for an energy-saving improvement through a simple-interest loan, i is the loan interest rate. If cash savings are used, i should be based on expected return from an alternative investment. You can make this more complicated than it is worth. For example, if money is borrowed through a home equity loan for which a tax deduction is made on interest payments, the accurate i should be the equity loan interest rate times (1 minus % tax bracket). But this level of detail is usually unnecessary given the other uncertainties involved, such as the fuel price inflation rate. Because of price volatility (see Table 5.4), it is hard to estimate fuel inflation.

The literature has debated the appropriate discount rate to use for evaluating energy systems and programs. Generally a value of 6%–8% is used for program evaluation (see Chapter 16). The time-value of money based on the discount rate is used in most of the methods of economic analysis described below.

5.4.3 Economic Measures of Cost-Effectiveness

Social and environmental factors drive some people to make sustainable energy choices, but economic factors are most important in driving widespread investment in more efficient and renewable energy systems and energy conserving behavior. There are several metrics used to assess economic cost-effectiveness and compare investments. These measures require energy analysis to evaluate energy savings of one option over another and the dollar value of energy saved. (For energy production systems, "energy savings" is the conventional energy avoided.) Most of these measures discount future dollar savings to present value.

SOLUTION

SOLUTION BOX 5.4

Simple Payback Period of Low-Flow Showerheads

When my family of five moved into our 50-year-old house, it had old high-flow showerheads. I thought of replacing them with low-flow showerheads, but I wanted to calculate the payback on the investment just to be sure it was a winner. Each new showerhead cost \$10. What is the simple payback period?

Solution:

To do the energy analysis, I measured the flow rates of the old and new showerheads: it took the old head 1 minute to fill a 5-gallon bucket, and it took the low-flow head 2.5 minutes to fill it. I stuck a thermometer in a comfortable shower and it was 100°F; when I ran just cold water it was 60°F. With my three teenage sons the average shower time was 10 minutes for the 25 showers per week the family took. I assumed my gas water heater operated at 75% efficiency, and I paid \$1 per therm for natural gas (NG) (1 therm = 100,000 Btu). Here are the energy analysis results:

Energy for Old Showerheads:

Flow rate = 5 gal/min

Flow time = 25 showers/wk × 10 min/shower × 52 wk/yr = 13,000 min/yr

Hot water flow = 5 gal/min × 13,000 min/yr = 65,000 gal/yr

Energy for hot water: Specific heat Equation 4.16

$$E = mc\Delta T = 65{,}000 \text{ gal/yr} \times 8.34 \text{ lb/gal} \times 1 \text{ Btu/lb-°F} \times (100°\text{F} - 60°\text{F}) = 21.7 \times 10^6 \text{ Btu/yr}$$

NG energy for hot water:

$$\eta = \frac{\text{useful hot water energy}}{\text{NG energy input}}$$

5.4.3.1 Simple Payback Period

The simple payback period (SPP) gives the number of years an energy efficiency improvement or production system will take to pay for its initial capital cost based on its energy and economic savings. It holds true for short time periods and/or low discount rates because it ignores the time-value of money and for minor operation and maintenance costs because it usually ignores them as well. Despite these limitations, SPP is one of the most intuitive and useful measures of cost-effectiveness.

$$\text{NG energy input} = \frac{\text{useful heating energy}}{\eta} = \frac{21.7 \times 10^6\ \text{Btu/yr}}{0.75} = 28.9 \times 10^6\ \text{Btu/yr}$$

Energy for New Showerheads:

Flow rate = 5 gal/2.5 min = 2 gal/min

Hot water flow = 2 gal/min × 13,000 min/yr = 26,000 gal/yr

Energy for hot water: Specific heat Equation 4.16

$$E = mc\Delta T = 26{,}000\ \text{gal/yr} \times 8.34\ \text{lb/gal} \times 1\ \text{Btu/lb-°F} \times (100°\text{F} - 60°\text{F}) = 8.68 \times 10^6\ \text{Btu/yr}$$

NG energy for hot water:

$$\text{NG energy input} = \frac{8.68 \times 10^6\ \text{Btu/yr}}{0.75} = 11.56 \times 10^6\ \text{Btu/yr}$$

Energy Savings:

$$\text{NG energy}_{\text{old}} - \text{NG energy}_{\text{low-flow}} = 28.9 - 11.56 = 17.34 \times 10^6\ \text{Btu/yr} = \text{AES}$$

So now I can calculate the SPP:

$$\text{SPP} = \frac{\text{IC}}{\text{AES} \times \text{Pr}} = \frac{\$10/\text{head} \times 3\ \text{heads}}{17.34 \times 10^6\ \text{Btu/yr} \times \$1/10^5\ \text{Btu}} = 0.173\ \text{yr} = 63\ \text{days}$$

This investment would be recovered by natural gas monetary savings in only 2 months, after which the savings would continue to accrue. If I had an electric water heater, the savings would be even more because electricity is more expensive per unit energy than natural gas (Table 5.4). Additional savings would come from reduced water bills.

Eq. 5.18 $$\text{Simple payback period (SPP, in years)} = \text{SPP} = \frac{\text{IC}}{\text{AES} \times \text{Pr}}$$

where IC = Initial capital cost, \$ (or cost difference between two options)
AES = Annual energy savings (e.g., kWh/yr, Btu/yr)
Pr = Energy price (e.g., \$/kWh, \$/Btu)

Solution Box 5.4 gives an example of the SPP of low-flow showerheads; we will carry this example through the various measures of economic cost-effectiveness.

5.4.3.2 Return on Investment

Return on investment (ROI) is a popular economic measure that is equal to the inverse of SPP. It tells what percentage of an investment will be returned in the first year. Generally an ROI greater than 10% is a good investment. We calculate it as follows:

Eq. 5.19 $$\textbf{Return on Investment (\%/year)} = \textbf{ROI} = \frac{100(\text{AES} \times \text{Pr})}{\text{IC}} = \frac{100}{\text{SPP}}$$

where AES = annual energy savings
P = price of saved energy
IC = initial capital cost

Returning to our example above, we can figure out the ROI of the investment in low-flow showerheads:

$$\text{ROI} = \frac{100}{\text{SPP}} = \frac{100}{0.173\text{yr}} = 580\% \text{ per year}$$

This of course is the kind of ROI most CEOs would be quite happy to report to their shareholders.

5.4.3.3 Cost of Conserved/Produced Energy

If we want to compare the cost of an energy investment to present or future energy prices, we want to know the cost of conserved energy (CCE), which measures the cost per unit of energy saved or produced by an efficiency or production investment over its lifetime. Annual operation and maintenance costs, if any, can be included. This measure considers the time-value of money through the capital recovery factor (CRF) using a discount rate. The CRF is the classic mortgage rate factor that spreads out a one-time dollar expense (like the price of a house or in our case the initial capital cost of an energy investment). The CRF and other useful economic analysis factors are defined in Sidebar 5.3. We can compute CCE as follows:

Eq. 5.20 $$\textbf{Cost of conserved energy (\$/energy unit)} = \textbf{CCE} = \frac{\text{IC} \times \text{CRF} + \text{O\&M}}{\text{AES}}$$

where IC = initial capital cost
CRF = capital recovery factor
O&M = annual operation and maintenance cost, $
AES = annual energy savings, energy unit/year

If O&M = 0, $\text{CCE} = \frac{\text{IC} \times \text{CRF}}{\text{AES}}$

The cost of conserved energy is an extremely useful economic measure because it calculates dollar/unit-energy that can be compared to existing or expecting energy rates or prices. It incorporates the time-value of money and annual operation and maintenance costs, if any. Solution Box 5.5 illustrates CCE calculation using our low-flow showerhead example.

SIDEBAR

SIDEBAR 5.3

Economic Analysis Factors

(Usually given as function buttons on a business calculator)

Compound Growth Factor (CGF) $= (1 + d)^n$ — Multiplied by dollar amount, CGF will grow that amount at annual compound rate d to year n. Inverse of PVF.

Present Value Factor (PVF) $= \dfrac{1}{(1 + d)^n}$ — Multiplied by dollar amount, PVF will discount that amount back **n** years at discount rate d. Inverse of CGF.

Capital Recovery Factor (CRF) $= \dfrac{d(1 + d)^n}{(1 - d)^n - 1}$ — Multiplied by dollar amount, it spreads that one-time cost over **n** years with equal annual payments; used to calculate annual mortgage payments. Inverse of UPVF.

Uniform Present Value Factor (UPVF) $= \dfrac{(1 - d)^n - 1}{d(1 + d)^n}$ — Takes an annual payment or monetary savings over **n** years and converts it with discounting to a lump present value. Inverse of CRF.

SOLUTION BOX 5.5

Cost of Conserved Energy of Low-Flow Showerheads

What is the cost of conserved energy for the low-flow showerhead investment given in Solution Box 5.4?

Solution:

Let's assume the life of the shower heads is 20 years, the discount rate is 3%, and O&M = 0.

$$\text{CRF} = \frac{d(1 + d)^n}{(1 - d)^n - 1} = \frac{0.03(1.03)^{20}}{(1.03)^{20} - 1} = \frac{0.054}{0.806} = 0.067$$

$$\text{CCE} = \frac{\text{IC} \times \text{CRF}}{\text{AES}} = \frac{\$30 \times 0.067}{(17.34 \times 10^6\ \text{Btu/yr} \times \dfrac{\text{therm}}{10^5\ \text{Btu}}} = \$0.01/\text{therm}$$

So for 20 years, this investment will conserve natural gas at an equivalent price of about 1¢ per therm compared to current price of $1 per therm. Anything lower than the current price is a good investment, but 1% of current price is a no-brainer.

SOLUTION

5.4.3.4 Present Value Life-Cycle Savings

Present value savings (PVS) calculates the total life-cycle dollar savings of the energy investment put in present-day dollars, based on the assumed discount rate (d). It can include annual operation and maintenance cost if appropriate. The future net annual dollar savings (assumed to be uniform each year) are discounted to present value by the uniform present value factor (UPVF) (see Sidebar 5.3) PVS can be compared to the total cost of the investment. Here's how it is calculated:

Eq. 5.21 $$\textbf{Present value savings} = \text{PVS} = (\text{AES} \times \text{Pr} - \text{O\&M}) \times \text{UPVF} \quad (\$)$$

where AES = annual energy savings, energy unit/yr
Pr = current energy price, \$/energy unit
O&M = annual operation and maintenance cost, \$/yr
UPVF = uniform present value factor, based on d

What is the PVS of the low-flow showerhead investment given above? Assume the life of the showerheads to be 20 years, a discount rate of 3%, and O&M = 0.

$$\text{UPVF} = \frac{(1-d)^n - 1}{d(1+d)^n} = \frac{(1.03)^{20} - 1}{0.03(1.03)^{20}} = \frac{0.806}{0.054} = \frac{1}{\text{CRF}} = 14.9$$

$$\text{PVS} = (\text{AES} \times \text{Pr} - \text{O\&M}) \times \text{UPVF} = (17.34 \times 10^6 \text{ Btu/yr} \times \$1/10^5 \text{ Btu} - 0) \times 14.9 = \$2584$$

Compared to the initial cost of \$30, this PVS of \$2584 looks mighty good!

5.4.3.5 Net Present Value over Life-Cycle

Net present value (NPV) is simply the difference between PVS over the life cycle and the initial capital cost of the investment. This gives us a simple measure of profit or earnings from the investment, considering the time-value of money. If the NPV is positive, the system is said to be cost-effective. Obviously, the larger the NPV, the better. It is calculated as follows:

Eq. 5.22 $$\textbf{Net present value } (\$) = \text{NPV} = \text{PVS} - \text{IC}$$

where PVS = present value savings (\$)
IC = initial capital cost (\$)

What is the PVS of the low-flow showerhead investment given in Solution Box 5.4?

$$\text{NPV} = \text{PVS} - \text{IC} = \$2584 - \$30 = \$2554$$

This still leaves our initial \$30 investment looking pretty good.

5.4.3.6 Benefit-Cost Ratio

The benefit-cost (B/C) ratio compares annualized dollar savings and annualized costs to provide a ratio of benefits to costs. If the B/C is greater than one, it indicates a cost-effective investment. Obviously, the larger the ratio, the better.

Eq. 5.23

$$\textbf{Benefit-cost ratio} = \frac{B}{C} = \frac{PVS}{IC}$$

where PVS = present value savings
IC = initial capital cost ($)

What is the B/C ratio for the low-flow showerhead investment given above?

$$\frac{B}{C} = \frac{PVS}{IC} = \frac{\$2584}{\$30} = \frac{86}{1} = 86$$

5.4.4 Performing Economic Analysis with Spreadsheets

These calculations are not too complicated, but they can be tedious given the number of economic factors. It is not surprising that economic analysts long ago produced tables, and more recently calculator functions and Internet multipliers to ease these menial calculations. We would like a means to perform these calculations easily so that we can vary our assumptions and produce different scenarios. Spreadsheets give us that capability, and we will use them in many of our analyses.

Table 5.5 gives a spreadsheet developed for energy and economic analysis. The beauty of a spreadsheet is that once the master is set up, it can be used for the analysis at hand. As the new data entries are made, new calculations are performed automatically. So it is easy to change an assumption, enter that value, and see all of the new results without actually doing a calculation. The spreadsheet is applied in our low-flow showerhead example. As you can see, the AES and Pr values are entered with the appropriate matching units. All values match our results from the previous sections.

5.4.5 Cost-Effectiveness and Market Penetration

So how do we interpret the results of economic analysis? What do we mean by the term *cost-effective*? How does cost-effectiveness drive economic behavior? At what point do people choose to invest in energy efficiency or renewable energy?

Technically, cost-effectiveness is defined as net positive economic value. Using our economic measures, cost-effectiveness is:

- Benefit-cost ratio greater than one, or when benefits exceed costs.
- Net present value greater than zero, indicating a positive bottom line.
- Present value savings greater than cost of investment.
- Cost of conserved energy (CCE) less than current or expected energy price. We can compare the CCE for a wide range of measures as well as their energy savings with the conservation supply curve, introduced in the following section.
- Simple payback period less than the life of the investment, understanding that future savings are neither inflated for energy price escalation nor discounted to present value.

table 5.5 Economic Analysis of Energy Systems and Efficiency Improvements

Using a spreadsheet to calculate cost-effectiveness, with the low-flow showerhead example

	Abbreviation	Value	Units	Formula in Value Column
Annual energy savings or production	AES	17.34	10^6 Btu/year	
Total cost	IC	30	$	
Energy price	Pr	10	$/$10^6$ Btu	
Annual operation and maintenance cost	O&M	0	$	
Energy price escalation rate	r	0.03	%/100	
Interest rate	i	0.06	%/100	
Discount rate*	d	0.03	%/100	$i - r$
Number of years	n	20	years	
Capital recovery factor*	CRF	0.0672		$d(1 + d)^n/[(1 + d)^n - 1]$
Compound growth factor*	CGF	1.8061		$(1 + d)^n$
Present value factor*	PVF	0.5537		$1/(1 + d)^n$
Uniform present value factor*	UPVF	14.8775		$[(1 + d)^n - 1]/d(1 + d)^n$
Today's value	P	100.00	$ or units	
Compound growth of present value*	F	180.61	$ or units	F = P * CGF
Present value of discounted future value*	P	100.00	$	P = F * PWF
Simple payback period*	SPP	0.173	years	SPP = IC/(AES * Pr)
Cost of conserved energy*	CCE	0.116	$/$10^6$ Btu	$CCE = \frac{IC * CRF + O\&M}{AES}$
Present value savings*	PVS	2580	$	PVS = (AES * Pr − O&M) * UPWF
Net present value*	NPV	2550	$	NPV = PVS − IC
Benefit-cost ratio*	BCR	86.0		$BCR = \frac{(AES * Pr - O\&M)}{(IC * CRF)}$

* Calculated values

We know that people face choices on how they invest their money. If we are to change our energy patterns on a large scale, renewable energy and efficiency must compete effectively against other investment choices. We need to know how cost-effectiveness translates to consumer choice and to market penetration. But we also know that people make choices based on other values. Full life-cycle analysis includes assessment of environmental effects, which we discuss later in this chapter. We will explore the broader issues of market penetration and transformation in Chapter 16.

5.4.6 Conservation Supply Curves for Efficiency and Savings

The conservation supply curve (CSC) was first popularized by Arthur Rosenfeld and Amory Lovins in the 1980s. It shows how different efficiency or production measures contribute to energy savings or supply, ordered by their cost-effectiveness measured by cost of conserved energy (CCE). Recall from Section 5.4.3.3 that CCE is annualized cost divided by annual energy savings produced and is given in cost/energy, such as ¢/kWh.

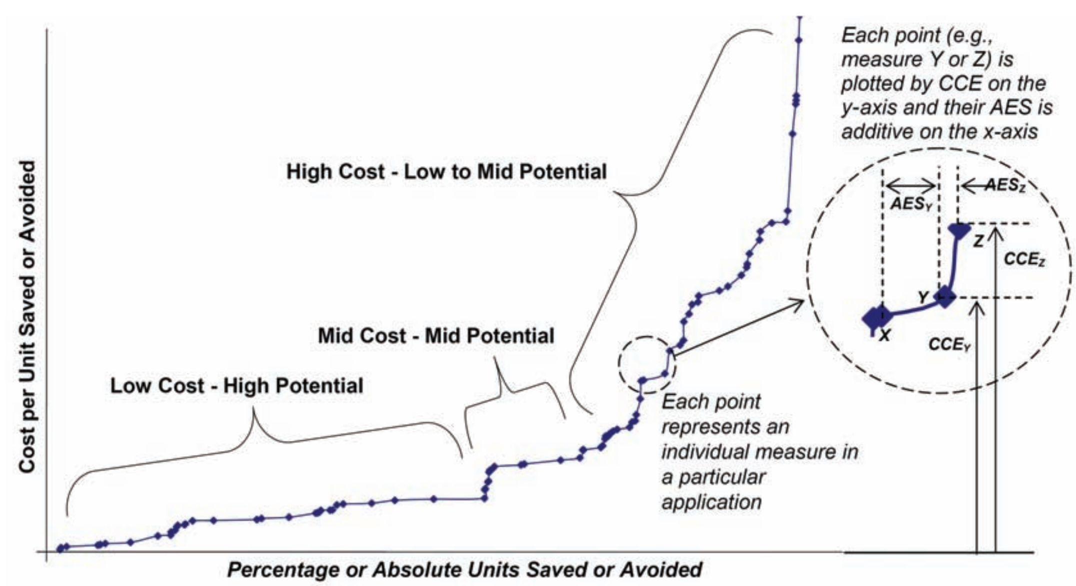
Figure 5.7 gives a hypothetical CSC, which illustrates the way the graph is developed. As shown in the inset, each point is plotted by a measure's CCE on the y-axis starting with the lowest-CCE, most cost-effective measures. The x-axis gives the cumulative energy savings of the measures, so that the graph becomes a step function. The CSC is elegant in its ability to combine economic and technical potential as well as to see both incremental and aggregate savings and costs.

Figures 5.8 and 5.9 give two examples of conservation supply curves from well-known studies.

Figure 5.8 is from a study of statewide electric efficiency potential in California funded by the Energy Foundation/Hewlett Foundation in 2002, right after the California electricity crisis (Rufo & Coito, 2002). As the figure shows, the study estimated that 10% of the state's projected base energy consumption could be saved at less than 5¢/kWh and 14% at less than 10¢/kWh.

Figure 5.9 gives an aggregate of 200 CSCs developed in 1993 representing U.S. national residential electricity measures and their potential savings. The study estimated that 400 TeraWh could be saved through efficiency measures costing less than 8¢/kWh, the national average residential electricity rate at the time (Stoft, 1995; Rosenfeld, 1993).

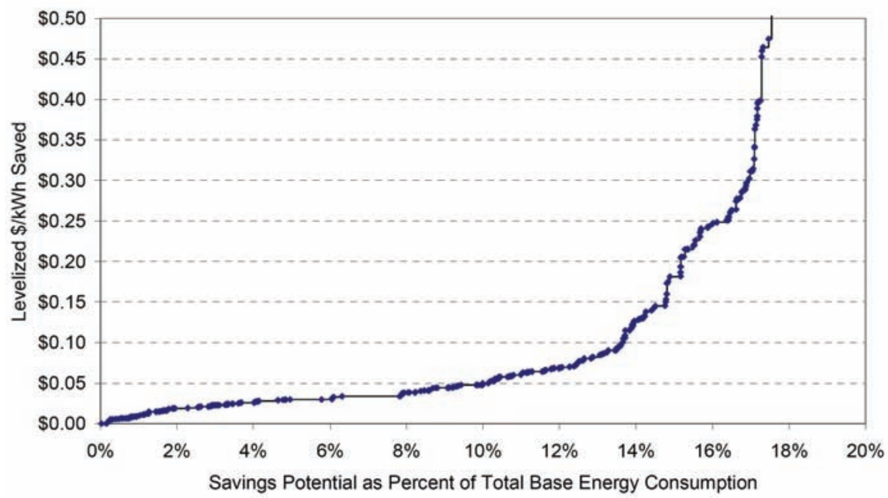
figure 5.7 **Hypothetical Conservation Supply Curve**



Plots energy measures' cost of conserved energy versus cumulative energy saved or avoided.

Source: Adapted from Rufo, 2003

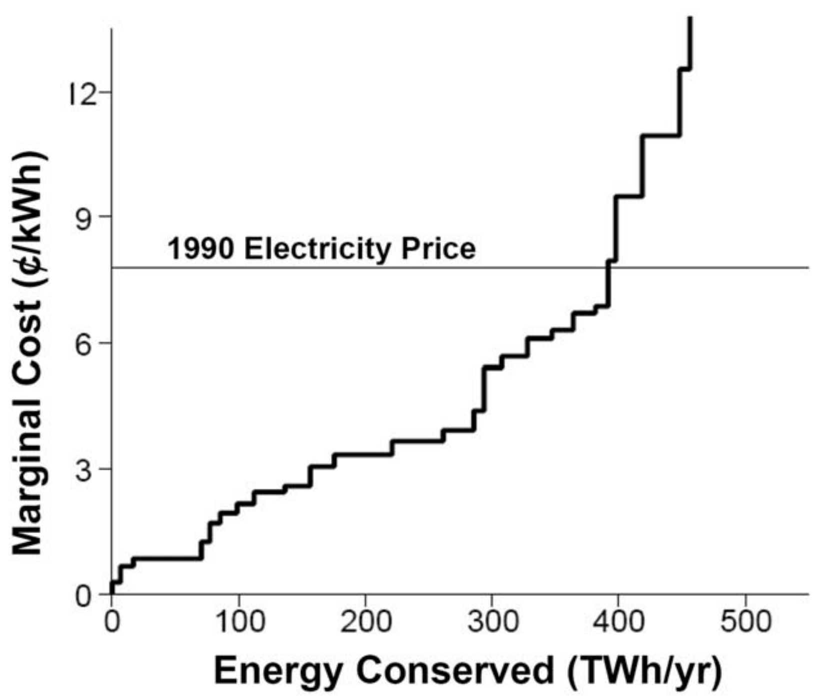
figure 5.8 **Conservation Supply Curve for California Electricity**



Graph shows a 10% savings for less than 5¢/kWh, 14% for less than 10¢/kWh.

SOURCE: Rufo and Coito, 2002

figure 5.9 **Conservation Supply Curve for U.S. Residential Electricity**



For less than the existing residential rates (at that time), 400 TeraWh could be saved.

SOURCE: Stoft, 1995; Rosenfeld, 1993

The conservation supply curve gives an excellent snapshot of the most cost-effective technologies, prioritizes them by both cost and energy benefit, and compares them to the existing price of energy or stated policy goals. However, some analysts have been critical of the wide use of CSC (Stoft, 2002) and CCE (Golove & Eto, 1996), and some of their concerns, listed below, should be considered when developing or using CSCs.

- A measure's energy savings is often overestimated.
- Energy savings from different measures are not always additive as CSC assumes.
- CCE usually underestimates the cost of implementing the savings by ignoring maintenance costs, transaction costs, and other barriers that must be overcome.
- It is difficult to predict accurately the future including future cost of other fuels to which CCE is compared, and the future capital cost or price of new technologies.

5.5 Environmental Analysis of Energy and Materials Systems

In addition to economic assessment, life-cycle analysis aims to evaluate the environmental implications of the energy and materials options. Energy extraction, transport, and use have a wide range of impacts on the environment. As we look to embodied energy in materials, we know that the acquisition, processing, transport, use, and disposal of various materials (e.g., steel, wood products, concrete, chemicals, agricultural products) have input energy and output environmental impact. Some of these impacts are regulated by government, and the cost of these regulations is usually passed on to consumers so it is reflected in the cost of energy. However, many of these effects are not regulated, appear as economic externalities, and are not fully accounted for in economic markets. Therefore, if we wish to allocate energy and material resources sustainably, we need to apply life-cycle analysis that incorporates both economic and environmental analysis and the short- and long-term cradle-to-grave impacts of energy and materials choices.

As discussed in Section 5.1.3 and shown in Figure 5.1, life-cycle analysis requires defining a system boundary and process as well as the inputs (e.g., materials, energy, water) and outputs (e.g., useful products as well as emissions, effluents, and waste) of the system from cradle to grave. The analysis requires inventory data of materials and energy used, and impact coefficients to determine the effects according to Equation 5.1:

Inventory data × Impact coefficient = Impact indicator

This section discusses sources and examples of environmental impact coefficients used for the life-cycle and environmental analysis. These coefficients give environmental impact per unit of energy or unit of material for various sources and uses. Just as we needed energy prices (e.g., $ per kWh) of various energy options to calculate economic costs of energy, we need environmental coefficients (e.g., impact per kWh) for different energy sources and materials to calculate environmental costs of energy and materials.

5.5.1 The NREL Life-Cycle Inventory

U.S. DOE's National Renewable Energy Laboratory (NREL) has partnered with ATHENA and Franklin to create a database of life-cycle inventory coefficients to be used in life-cycle analysis. This is a work in progress, but already the project has generated useful data for the long list of products and processes given in Table 5.6.

For each product or process, input and output coefficients are provided in the format given in Table 5.7, which shows petroleum refining. For each 1000 pounds of petroleum products, the table gives the materials and energy inputs, the emissions and waste outputs, and product and co-product outputs. The data are provided in downloadable spreadsheet format for easy access and integration into life-cycle analyses. See http://www.nrel.gov/lci.

How do we use the life-cycle inventory? For example, if I drive 15,000 miles per year and get 20 mpg, I can figure out the crude oil and electricity, emissions of SO_x and NO_x, chemical oxygen demand (COD) effluent, and solid waste associated with refining the gasoline I consume each year.

For 15,000 mpy, 20 mpg, and gasoline at 6.25 lb/gal, I can calculate my gasoline use:

$$\frac{15{,}000 \text{ mi/yr}}{20 \text{ mi/gal}} = 750\,\frac{\text{gal}}{\text{yr}} \times 6.25\,\frac{\text{lb}}{\text{gal}} = 4688\,\frac{\text{lb}}{\text{yr}} \text{ gasoline (this is my inventory data)}$$

We can find impact coefficients for gasoline from Table 5.7 by multiplying the overall coefficients by 0.421, the proportional output of gasoline for each pound of petroleum products. So my use requires:

$$\text{Crude oil} = \frac{1034 \text{ lb crude/1000 lb prod.}}{421 \text{ lb gas/1000 lb prod.}} \times \frac{4688 \text{ lb gas}}{\text{year}} = \frac{11{,}514 \text{ lb crude/yr}}{7.5 \text{ lb crude/gal} \times 42 \text{ gal/bbl}}$$
$$= 36.5 \text{ bbl crude}$$

table 5.6 Selected Processes and Products Included in NREL Life-Cycle Inventory Database

Agricultural Products

Corn production
Rapeseed production
Soybean production

Building and Construction Products

Glue laminated beam (Glulam), PNW at mill gate
Oriented strand board (OSB), SE at mill gate
Plywood, PNW at mill gate
Softwood lumber (dry), PNW at mill

Electricity Generation
Materials Used in Manufacturing of Automobiles/Durables

Cold rolled sheet production
Primary aluminum production

Primary Fuel Combustion

Biomass combustion in utility turbines
Bituminous coal combustion in utility boilers
Distillate oil combustion in utility boilers
Natural gas combustion in utility boilers
Wood combustion

Primary Fuel Production

Bituminous coal production
Crude oil extraction
Natural gas extraction and processing
Petroleum refining
Uranium fuel production

Transportation

Cargo plane transportation
Diesel-fueled single unit truck transportation

table 5.7 Sample Data from NREL Life-Cycle Inventory Database: Inputs and Outputs from Petroleum Refining

1000 lb Products	Name Unit	Category	Units	Petroleum Refining
Inputs from technosphere (for each 1000 lb petroleum output)	Crude oil		lb	1034.00
	Electricity		kWh	62.66
	LPG		gal	0.11
	Natural gas		ft^3	146.60
	Residual oil		gal	2.69
	Barge		ton-mi	0.37
	Ocean freighter		ton-mi	1472.00
	Pipeline		ton-mi	136.00
Inputs from nature				
Outputs to nature (for each 1000 lb petroleum output)	Aldehydes	air	lb	0.04
	Ammonia	air	lb	0.02
	Carbon monoxide	air	lb	13.30
	HC (other than CH_4)	air	lb	2.03
	Methane	air	lb	0.07
	NO_x	air	lb	0.33
	Particulate	air	lb	0.24
	SO_x	air	lb	2.35
	COD	water	lb	0.23
	Nitrogen (as NH_3)	water	lb	0.02
	Oil/grease	water	lb	0.01
	TSS	water	lb	0.03
	Solid waste	waste management	lb	5.60
Product/co-product outputs (and fraction of outputs to nature)	Distillate fuel oil (0.219)		lb	219.00
	LPG (0.027)		lb	27.00
	Gasoline (0.421)		lb	421.00
	Residual fuel oil (0.049)		lb	49.00
	Asphalt/road oil (0.037)		lb	37.00
	Kerosene/jet fuel (0.091)		lb	91.00
	Petroleum coke (0.060)		lb	60.00
	Still gas (0.045)		lb	45.00
	Other (0.052)		lb	52.00
	Total petroleum products (1.000)		lb	1000.00

This is the crude oil required to refine the gasoline I use. There are other useful petroleum co-products produced in the refining process, and although this entire amount is needed for my gasoline, the oil associated with just my gasoline is 36.5 bbls/yr × 0.421 = 15.4 bbls/yr.

- **Electricity = 62.66 kWh/1034 lb crude × 11,514 lb crude = 698 kWh**
  (698 × 0.421 = 294 kWh associated with my gasoline)
- **SO_x = 2.35 lb SO_x/1034 lb crude × 11,514 lb crude = 26 lb SO_x**
  (11 lb for my gasoline)
- **NO_x = 0.33 lb NO_x/1034 lb crude × 11,514 lb crude = 3.7 lb NO_x**
  (1.5 lb for my gasoline)
- **COD = 0.23 lb COD/1034 lb crude × 11,514 lb crude = 2.6 lb COD**
  (1.1 lb for my gasoline)
- **Solid waste = 5.6 lb SW/1034 lb crude × 11,514 lb crude = 62 lb SW**
  (26 lb for my gasoline)

As NREL's LCI and other life-cycle databases are developed further, we will be able to enhance assessment of energy options and better recognize their environmental implications.

5.5.2 Air Pollutant and Carbon Emissions from Combustion of Fossil Fuels

Perhaps the most severe of the environmental impacts of current energy use is the air pollution emitted from the combustion of fossil fuels. As shown in Table 2.4, energy use accounts for 90% of air pollution emissions in the United States, about 20% from stationary sources, mostly power plants, and 70% from mobile sources, mostly passenger vehicles. Much progress has been made to reduce emissions through technological controls during the past 30 years. Indeed, total emissions are less than half of what they were in 1970 despite increases in population, vehicle miles traveled, and the economy. Still, many cities have not attained national clean air standards, and additional progress is needed.

Increasing attention has been given to emissions of carbon dioxide and other GHG from fossil fuels, because of the impacts associated with global climate change. These emissions are not yet regulated in the United States, but they have become an important part of environmental accounting for energy use. Indeed, the "carbon footprint," or the carbon emissions associated with a person's or a community's energy use patterns, has become a useful overall indicator of environmental impact of energy use. Table 5.8 gives CO_2 emission rates for various fuels. Of the fossil fuels, natural gas has the lowest rate, about 75% of oil products and 57% of coal. Biomass combustion is considered carbon neutral because it emits "biogenic" CO_2 or CO_2 recently absorbed by vegetation from the atmosphere.

Let's look at some emissions impact coefficients or rates associated with two important energy uses, electricity and buildings. We will discuss transportation emissions rates in Chapter 13. At the end of this section we explore the increasingly popular approach to calculate a household's "carbon footprint" calculations and estimating remediation to offset those footprint emissions through Green Tags and tree planting.

table 5.8 CO_2 Emission Rates, Various Fuel Combustion

Fuel	Pounds CO_2 per unit	Pounds CO_2 per 10^6 Btu
Motor gasoline	19.56 per gal	156.4
Distillate and diesel	22.38 per gal	161.4
Natural gas	120.6 per 10^3 ft^3	117.1
Coal (bituminous)	4931 per short ton	205.3
Biomass*	0	0

* Biomass contains "biogenic" carbon. Under international greenhouse gas accounting methods developed by the Intergovernmental Panel on Climate Change, biogenic carbon is part of the natural carbon balance and it will not add to atmospheric concentrations of carbon dioxide.
Source: U.S. EIA: http://www.eia.doe.gov/oiaf/1605/coefficients.html

5.5.2.1 Emissions Rates for Electricity

Table 5.9 gives emissions rates for electricity generation for coal, oil, and natural gas, as well as national average rates and rates for non–fossil fuel generation. Coal has the highest emissions rates for all pollutants. Compared to coal, the natural gas emission rate is 62% for CO_2, 28% for NO_x, and less than 1% for SO_x. Wood and MSW generation produce NO_x and CO_2, but the CO_2 emitted is "contemporary" not "fossil" carbon, so it is considered part of the natural contemporary carbon cycle. In other words, the carbon in wood and paper (the main combustible part of MSW) was recently atmospheric CO_2 photosynthesized in wood products, and it is released back to the atmosphere during combustion. MSW plants give off trace amounts of mercury and, depending on the constituents of the waste stream, may release potentially toxic emissions such as dioxins.

Of course, the national averages may not be too precise for a given location that is usually served by a unique mixture of power sources from the grid. EPA's **eGRID database** gives emissions rates for each state based on the state's mix of power generation. Table 5.10 gives rates from the database for four states. The rates reflect the mix of sources of power in Washington (76% hydro, 9% nuclear, 8% coal), California (49% natural gas, 19% nuclear, 17% hydro, 12% wind/geothermal), Virginia (51% coal, 37% nuclear), and West Virginia

table 5.9 U.S. Average Emissions Rates for Different Sources of Electricity (lb per MWh)

	National Average	Coal	Natural Gas*	Oil	MSW	Biomass	Hydro	Nuclear	Solar/Wind	Geothermal
CO_2	1392	2249	1135	1672	1500**	1500**	~0	~0	~0	~0
SO_x	6	13	0.1	12	negl	negl	~0	~0	~0	negligible
NO_x	3	6	1.7	4	2.0	2.0	~0	~0	~0	~0
Mercury (lb/GWh)	0.03	0.06	–	–	trace**	–	–	–	–	–

* Rates for combustion turbine; combined cycle systems have one-third lower emissions rates
** Not considered GHG-CO_2 because it is part of contemporary carbon cycle. Also, potential trace amounts of other toxin emissions such as dioxins.

table 5.10 **Average Emissions Rates for Selected States' Generation of Electricity, lb per MWh**

	Washington	California	Virginia	West Virginia
CO_2	287	633	1232	2027
SO_x	1.6	0.17	5.8	12.9
NO_x	0.6	0.56	2.6	5.8
Hg (lb/GWh)	0.006	0.002	0.02	0.05

(98% coal). See the eGRID database for emissions rates for other states (http://www.epa.gov/cleanenergy/egrid/index.htm).

The example in Solution Box 5.6 shows that environmental impacts of electricity obviously depend not only on consumption, but also on the source of that power. Check out EPA's "Power Profiler," an interactive online calculator that performs impact calculations for users by simply submitting their zip code and monthly electricity use (see http://www.epa.gov/cleanenergy/powerprofiler.htm).

5.5.2.2 Carbon Emissions Rates for Buildings

Emissions from building operations are more difficult to assess because of the variety of operating conditions. For example, gas and oil heating systems give off NO^+, PM, and CO_2, but their emission rates are very dependent on the system size, type, age, and condition. Electricity use in buildings does not emit air pollutants or CO_2 directly, but that use may require significant emissions back up the transmission wire at the power plant. Emissions from electricity use in buildings can be determined from the emissions rates described in Section 5.5.2.1. The CO_2 emission rates per unit of fuel for various fuels used in buildings are given in the CO_2 calculator shown in Table 5.12. We discuss methods of calculating building heating fuel use in Chapter 6 and building electricity use in Chapter 8.

5.5.2.3 Emissions Rates for Transportation

Transportation mobile sources are the main source of urban air pollution. They contribute about half of the nation's NO_x and volatile organic compounds (VOC), which combine to form photochemical smog. Transportation vehicles also contribute about one-third of the CO_2 emissions in the United States. Chapter 13 discusses emissions rates and standards for vehicles.

5.5.3 Assessing Other Environmental Impacts of Energy Use

In addition to air quality and climate change, there are many other environmental impacts of energy use but they are not as easy to assess as air emissions. Table 2.5 illustrates the wide range of impacts and qualifies them in severity and risk.

SOLUTION BOX 5.6

Calculating Emissions from Electricity Consumption

SOLUTION

Let's say the authors' households each consume an average of 500 kWh per month. What are the annual emissions attributed to electricity consumption in each household?

Solution:

Masters spends time in both Washington and California, so we'll calculate emissions for both states. Randolph lives in Virginia, but is served by American Electric Power, which generates most of its power in West Virginia, so we should use the West Virginia emissions rate.

Their annual electricity consumption is 500 kWh/mo × 12 mo = 6000 kWh = 6 MWh. In Washington the CO_2 emissions for that use are 287 lb/MWh × 6 MWh = 1722 lb. In West Virginia, the CO_2 emissions are 2027 lb/MWh × 6 MWh = 12,162 lb **or 8 times that of Washington!** Table 5.11 gives solution results for other emissions and for California.

table 5.11 **Annual Emissions (lb) Attributable to 500 kWh/mo Electricity Consumption**

	Washington	California	West Virginia
CO_2	1722	3798	12,162
SO_x	9.6	1.0	77.8
NO_x	3.6	3.4	34.8
Hg (10^{-3} lb)	0.04	0.01	0.30

5.5.4 Calculating Your Carbon Footprint

With the increased interest in global climate change, more people are interested in determining the effect their energy consumption has on greenhouse gas (GHG) emissions, and then taking measures to reduce or offset those emissions. They can reduce emissions by employing energy efficiency and conservation and on-site renewable energy systems or by buying "green power" from an electricity supplier. Not all consumers have access to green power, but all consumers can buy Green Tags (also called Renewable Energy Certificates), which are a proxy for green power. Consumers buy these Green Tags in 1000 kWh bundles and the revenues are using to develop renewable electricity. Green power and Green Tags are discussed in Chapter 18. Consumers can also offset their CO_2 emissions by planting trees.

To help consumers assess their carbon emissions, several groups have developed carbon calculators, applying the concept of the ecological footprint to carbon emissions. The ecological footprint approach aims to calculate a person or household's impact on the

table 5.12 Carbon Dioxide Emissions Calculator and Offsets from Green Tags and Tree Planting

CO_2 Emission Coefficients	Pounds CO_2		
Petroleum Products	**per gal**	**per 10^6 Btu**	**Other coefficients:**
Motor gasoline	19.6	156.4	33.4 aviation passenger mile per gal
Distillate/diesel fuel	22.4	161.4	0.63 lb CO_2 per aviation passenger mile
Jet fuel	21.1	156.3	1400 lb CO_2 offset per 1000 kWh Green Tag
Kerosene	21.5	159.5	667 lb CO_2 offset per tree planted
Liquefied petroleum gases	12.8	139.0	
Residual fuel	26.0	173.9	
Propane	12.7	139.2	
E-85*	3.7	29.7	
B-20 biodiesel*	17.9	129.1	
Gaseous Fuels	**per 1000 ft^3**	**per 10^6 Btu**	
Methane	116.4	115.3	
Flare gas	133.8	120.7	
Natural gas	120.6	117.1	
Coal	**per short ton**	**per 10^6 Btu**	
Anthracite	3852.2	227.4	
Bituminous	4931.3	205.3	
Subbituminous	3715.9	212.7	
Lignite	2791.6	215.4	
Electricity	**per MWh**	**per 10^6 Btu**	
National average	1392	408.0	
Coal	2249	659.1	
Natural gas	1135	332.6	
Oil	1672	490.0	
MSW*	1500	439.6	
Biomass*	1500	439.6	
Geothermal energy	0	0	
Wind	0	0	
Photovoltaic and solar thermal	0	0	
Hydropower	0	0	
Nuclear	0	0	

Table 5.12 Continued

Energy Use Carbon Footprint and Remediation Offsets

	Energy Use or Activity	Efficiency	CO_2 Coefficient	CO_2 Emissions & Offsets*
Electricity	11,256 kWh/yr		1.392 lb/kWh	15,668 lb/yr
Natural gas	831 therms/yr		11.7 lb/therm	9728 lb/yr
Fuel oil	0 gal/yr		22.4 lb/gal	0 lb/yr
Propane	0 gal/yr		13.9 lb/gal	0 lb/yr
Vehicle 1—gasoline	13,900 mi/yr	25 mpg	19.6 lb/gal	10,898 lb/yr
Vehicle 2—diesel	0 mi/yr	35 mpg	22.4 lb/gal	0 lb/yr
Air travel	962 mi/yr		0.63 lb/pass. mi	606 lb/yr
Total				**36,900 lb/yr**
Offset—Green Tags = total CO_2/offset rate			**1400 lb/1000 kWh**	**26 Green Tags**
Offset—Tree Planting = total CO_2/offset rate			**667 lb/tree**	**55 Trees planted**

* Emissions depend on make-up of waste or biomass. Actual emissions are given, but biomass contain "biogenic" carbon. Under international greenhouse gas accounting methods developed by the Intergovernmental Panel on Climate Change, biogenic carbon is part of the natural carbon balance, and it will not add to atmospheric concentrations of carbon dioxide.

environment in terms of consumption of materials and energy and generation of emissions and wastes. The carbon footprint focuses on the CO_2 emissions from energy consumption. The calculation is useful to see the magnitude of impact and ways to reduce household CO_2 emissions, but it can also determine the mitigation offsets needed through Green Tags, tree planting, or other mitigation to become "carbon neutral." A carbon neutral household is one in which its mitigation measures offset its carbon emissions.

Table 5.12 gives a spreadsheet giving CO_2 emissions coefficients for various energy sources. The portion of the spreadsheet on this page gives an energy use carbon footprint and remediation offsets. Given energy use for household heating and electricity, vehicle use, and air travel, the spreadsheet calculates total emissions per year and the Green Tags and trees planted that would offset the CO_2 emissions.

The default values given for energy use for electricity, natural gas, vehicle gasoline, and air travel are U.S. national averages. The average household produces 36,900 lb CO_2/yr. These emissions could be offset by the purchase of twenty-six Green Tags or the planting of fifty-five trees. The spreadsheet can be used for any energy use for fuels and sources for which emissions coefficients are given. As we know from Section 5.5.2.1, electricity emissions rates vary for different states, so specific state rates from EPA's eGRID database should be used.

5.6 Summary

This chapter described several methods of life-cycle, energy, economic, and environmental analysis that are important to compare energy and materials options and make informed decisions. Energy analysis is important to understand how much energy is used, the efficiency of use, and also how much energy it takes to produce energy. Once energy use requirements are known, economic analysis evaluates relative cost-effectiveness. Several techniques are available, but the most straightforward is simple payback period. Discounting future savings is important for long time periods and high discount rates. Spreadsheets are very useful in performing economic analyses, especially with varying assumptions.

Environmental assessment adds an important sustainability dimension to energy and economic analysis. Assessing air and carbon emissions of energy options using emissions factors or coefficients is more advanced than assessing other environmental impacts, such as water and land pollution.

Life-cycle analysis combines energy, economic, and environmental analysis to assess the broad impacts of energy and materials options from cradle-to-grave or from the first step in resource acquisition to the last step of deconstruction and waste disposal. Life-cycle analysis is not yet fully integrated into common practice, but recent developments indicate improved analytical tools and data for what may come to be called "sustainability analysis."

Market penetration of new energy-saving technologies tends to require very short payback periods because of competing investment opportunities. Improved information, access to capital, and government policies can help overcome transaction costs and other barriers to penetration of efficient and renewable energy technologies. Market penetration and the role of public policy are discussed in Chapter 16.