Measuring Changes in Energy Efficiency for the *Annual Energy Outlook 2002*

by
Steven H. Wade

This paper describes the construction of an aggregate energy efficiency index based on projections of sectoral and subsector energy consumption and subsector-specific energy service indicators. The results are compared with the ratio energy to real gross domestic product, which typically is presented as a measure of energy intensity.

Introduction

Energy efficiency and conservation are currently important components of the debate about the direction of future energy policy. Measuring the *actual* energy efficiency of the U.S. economy is a daunting task because of the immense data requirements for a proper calculation. Appropriate data are difficult to obtain, and as a result historical descriptions of the economy usually are summarized in two energy intensity measures: (1) energy consumption per dollar of real gross domestic product (GDP) and (2) energy consumption per capita. In general, these energy intensity measures can be quite different from measures of energy efficiency. However, the energy projections from the National Energy Modeling System (NEMS) provide the required specificity to develop detailed estimates of *projected* energy efficiency.[1,2]

This paper describes the methodology used to develop the NEMS estimate of projected aggregate energy efficiency and to describe the results of applying it to the *Annual Energy Outlook 2002 (AEO2002)* reference case.[3] The method uses an indexing procedure applied to subsectors of five broad sectors defined by the four end-use consumption modules (residential, commercial, industrial, and transportation) and the electricity generation module of NEMS. These five sectors account for all energy consumption and conversion losses in the economy. When electricity generators are included as a fifth sector, the proper measure of electricity consumption for the end-use sectors is site consumption.[4] This accounting framework assigns changes in generation efficiency directly to the electricity generation sector.

The efficiency calculations described in this paper produce an aggregate composite efficiency index (ACEI) based on some 2,500 detailed subsector components. As part of the calculations, intermediate calculations of individual sector efficiency indexes are also developed. For some sectors, reliance on readily available reported results is sufficient to develop the efficiency estimates. In other cases, additional accounting variables are added to the appropriate modules to preserve important dimensions or characteristics for the calculations that are made at the end of a model run. Specific details are described for each sector in the methodology and results sections below.

[1]The NEMS projections are based on detailed end use and technology information that is not available annually for the U.S. economy. For example, NEMS provides projections of residential space heating energy consumption and stock efficiency for heat pumps in single-family homes in the South Atlantic Census Division on a year-by-year basis. This type of information is not collected on an annual basis.

[2]For additional information on NEMS, see Energy Information Administration, *National Energy Modeling System, An Overview 2000*, DOE/EIA-0581(2000) (Washington, DC, March 2000), web site www.eia.doe.gov/oiaf/aeo/overview/index.html. Details on individual modules are available in recent model documentation reports at web site www.eia.doe.gov/bookshelf/docs.html.

[3]Energy Information Administration, *Annual Energy Outlook 2002*, DOE/EIA-0383(2002) (Washington, DC, December 2001), web site www.eia.doe.gov/oiaf/aeo/index.html.

[4]Site electricity consumption refers to electricity consumption as it would be registered by a customer's meter. Another method for measuring end-use electricity consumption is to include the electric conversion and transmission and distribution losses that were incurred in supplying the electricity to the customer. This concept is called "primary energy consumption for electricity." If the electricity generation sector were not explicitly treated, then primary energy would be the appropriate concept; however, when primary energy is modeled and the generation sector is not explicitly treated, any efficiency gains in generation are inappropriately attributed to the end-use sectors.

Examples of Energy Efficiency Concepts

Energy efficiency means different things for different people and therefore needs to be carefully defined. In the context of this effort, energy efficiency is defined as the ratio of the amount of energy services provided to the amount of energy consumed.[5] Thus, using less energy to provide the same level of energy services or obtaining more energy services from the same energy input is defined as an efficiency gain. Energy conservation is defined as reducing energy consumption through a reduction in the amount of energy services consumed. Conservation measures leave the ratio of energy services to energy consumption unchanged and thus do not affect efficiency.

Using residential space heating as an example, replacing an old, inefficient natural gas furnace with a newer, more efficient one is an example of an efficiency increase and would be considered as such by virtually anyone's definition. Turning down the thermostat in the winter but doing nothing else would generally be considered a conservation measure, but it might also be considered more efficient living. Installing more attic insulation might be considered a conservation measure by some because it allows less natural gas to be used for heating with the existing furnace (i.e., the efficiency of the furnace is not changed); however, adding insulation can be viewed as an efficiency gain to the building shell. When the concept of energy service is defined more generally as interior warmth—a service produced by the combination of the heating equipment and the building envelope—adding insulation fits the definition of an efficiency increase. That is, maintaining a constant level of interior warmth (thermostat setting) after the addition of insulation can be accomplished using fewer British thermal units (Btu) of fuel input than before. This is the definition of energy efficiency used in this paper.

Installing a time-of-day thermostat is considered here to be an energy conservation measure rather than an efficiency gain. With a time-of-day thermostat, when heat is not needed (for example, when the house is unoccupied or when the occupants are sleeping), the temperature can be reduced with no one noticing, and less energy is consumed. One could view this measure as providing less energy service and thus being defined as a conservation measure. Alternatively, one could view it as an efficiency gain, because energy services *to the occupants* are unchanged or unnoticed. Because less energy service is actually provided (noticed or unnoticed), this example is classified as a conservation measure for the purposes of this paper. Some measures might appropriately be classified either as efficiency gains or as conservation measures, depending on the point of view.

Energy intensity is a related, but distinct, concept. Energy intensity is generally defined as the amount of energy consumption per unit of GDP or another indicator that is serving as a rough proxy for energy services provided. Energy intensities are often broadly defined concepts applied either to an entire sector of the economy or even the economy as a whole. For example, residential sector energy intensity can be defined as residential energy consumption per household or per square foot. Economy-wide intensity concepts described here are either energy consumption per unit of real GDP or energy consumption per capita.

Note that energy consumption is in the numerator of the ratio in the definition of energy intensity, whereas the definition of energy efficiency places energy consumption or energy input in the denominator. Consequently, the concepts are inversely related, and, other factors being equal, an increase in energy efficiency will reduce energy intensity. However, changes in energy intensity may occur without any underlying changes in energy efficiency due to conservation, structural shifts between sectors or regions of the economy (e.g., a shift toward less energy-intensive industries or a population migration to warmer climates) , or changes in the mix of activities within sectors. These are just a few factors that can affect energy intensity without changing efficiency. To frame the differences between energy efficiency, conservation, and energy intensity, further examples and discussion follow.

Example 1: In the *AEO2002* reference case, the fuel efficiency (miles per gallon) of the light-duty vehicle (LDV) fleet is projected to increase by an average of 0.3 percent annually between 2000 and 2020.[6] Whether the LDV fleet miles per gallon is an appropriate estimate of efficiency change depends on how the energy service is defined.

Discussion: Two components of the LDV fleet—passenger cars and light trucks—account for 99.8 percent of its energy consumption (motorcycles are the remainder and do not have a significant effect on the calculations). For passenger cars, average fleet fuel efficiency is projected to increase from 21.6 miles per gallon in 2000 to 24.6 miles per gallon in 2020, an average annual rate of

[5]This is a typical definition of energy efficiency. For a thorough discussion of the issues involved in measuring efficiency, see Energy Information Administration, *Measuring Energy Efficiency in the United States' Economy: A Beginning*, DOE / EIA-0555(95) / 2 (Washington, DC, October 1995); web site www.eia.doe.gov / emeu / efficiency / contents.html; and S.J. Battles and E.M. Burns, "United States Energy Usage and Efficiency: Measuring Changes Over Time," Presented at the 17th Congress of the World Energy Council (Houston TX, September 14, 1998), web site www.eia.doe.gov / emeu / efficiency / wec98.htm.

[6]The LDV fleet includes cars, light trucks (sport utility vehicles, pickup trucks, and vans), and motorcycles.

0.7 percent. For light trucks, average fleet fuel efficiency is projected to increase from 17.1 miles per gallon to 18.2 miles per gallon, an average annual rate of 0.3 percent. At the same time, the mix of vehicles in the fleet is expected to shift in favor of the larger, less fuel-efficient light truck component. Light trucks accounted for 42 percent of total LDV energy consumption in 2000, but in 2020 they are projected to account for 56 percent of the total. As a result, when the energy service provided by the two vehicle categories is considered to be the same (that is, when energy efficiency is calculated for the LDV fleet as a whole, as it was in the statement of this example), the expected shift to less efficient light trucks reduces the projected overall increase in fleet efficiency to an average of 0.3 percent per year.

The calculation of separate efficiency indexes for cars and light trucks would be appropriate if one assumed that consumers value the energy services received from light trucks differently from those received from passenger cars,[7] and, therefore, that cars and light trucks should be considered as separate end-use categories. When this assumption is made, calculation of the projected rate of increase in energy efficiency for LDVs as a whole involves weighting the expected increases for the two components by their expected proportions of combined energy consumption. This is the method adopted in this paper, resulting in a calculated rate of 0.5 percent per year—significantly higher than the 0.3-percent average annual increase that is projected when all LDVs are considered as a single end-use category providing the same energy service.

Example 2: In order to reduce energy consumption, a homeowner replaces several incandescent light bulbs with compact fluorescent bulbs.

Discussion: The efficiency calculations assume that the energy services are comparable for these two lighting technologies.[8] Under this assumption, the consumer obtains the same light output but in the process uses only about one-fourth as much electricity. This type of change fits the definition of an efficiency improvement. Such a shift would also contribute to lower energy intensity.

Example 3: In response to rising energy prices, a company decides to adjust its thermostat settings in order to use less energy.

Discussion: Because the change is made in response to prices, it can be considered to be a component of the short-run price elasticity of demand.[9] This type of change is considered a conservation measure and not an efficiency improvement. It would also lower energy intensity measures.

Example 4: A homeowner switches from a natural gas furnace and central air conditioning to an electric heat pump. For purposes of this example, any effects on cooling energy consumption due to the replacement of a furnace with a heat pump are ignored.

Discussion: An older natural gas furnace in a colder climate will consume roughly 2.5 to 3 times as many Btu on-site as a heat pump.[10] Thus, site Btu consumption will decrease. A narrow view of energy efficiency would cause this replacement to be judged as an efficiency gain, even though total Btu in the economy would reflect a much smaller decrease and could even increase.[11] For the building sector efficiency calculations, end-use services have been defined as fuel specific. That is, for the calculations, there is an electric space heating end use as well as a natural gas space heating end use.[12] In the current replacement example, each combination of space heating end use and fuel is given its own efficiency calculation. This is similar to the car and light truck example, where the services were considered to be different. In this example, fuel switching alone will not result in changes in efficiency.

The effects on energy intensity depend on the efficiency with which electricity is produced and delivered. In 2000, a kilowatthour of electricity at the end-use level on average represented 3.2 times as many Btu as the Btu

[7]This assumption is bolstered by the increasing popularity of sport utility vehicles despite their higher prices. Possible differences between the transportation services provided by light trucks and those provided by cars include increased safety in collisions with smaller vehicles, better view of the road, four-wheel drive capability, and larger cargo capacity.

[8]As for many of the assumptions made in the implementation of the efficiency calculations, this assumption could also be debated. Some might argue that compact fluorescent bulbs do not actually produce energy services equivalent to incandescent bulbs because their light is not as pleasing to some, and when they are first started, their output does not reach full intensity immediately.

[9]There may be other short-run responses to rising energy prices, such as reducing water heater temperatures or cutting back on non-task lighting.

[10]This is a difference in site energy consumption and is obtained by converting kilowatthours from a homeowner's electricity bill to Btu using the Btu content of electricity of 3,412 Btu per kilowatthour.

[11]At the economy level, replacing a fuel-based furnace with an electric heat pump requires additional electricity generation and the attendant conversion losses and transmission and distribution losses.

[12]This is another example of a choice that is debatable. It is made here for two reasons. First, by defining separate end uses for each space heating fuel, the efficiency calculations become "fuel neutral." That is, a shift in fuel preference will have virtually no effect on measured energy efficiency. Second, certain consumers prefer one space heating fuel to another. By exhibiting a preference, consumers express the view that the energy services are indeed different.

content of the electricity used at the site.[13] Depending on the actual consumption of the electric heat pump, energy intensity could increase, decrease, or remain about the same.

Example 5: New homes have recently tended to be larger on average than existing homes and have been increasing in size year by year.

Discussion: This is an example of increased services being provided for the larger homes. When energy consumption for space conditioning is computed, it is normalized for square footage before the efficiency calculations are made. The result of this procedure is that two homes differing only in floorspace area (i.e., having the same type of heating and cooling equipment, the same lighting types and lumens levels, the same insulation levels, etc.) will have the same energy consumption per square foot and thus the same measured efficiency. If consumption per household had been chosen as the measure of energy efficiency (instead of consumption per square foot), then the larger home would be judged less efficient. All else being equal, larger homes do require increased energy consumption and will thus affect energy intensity.[14]

Methodology

Aggregation and a Numerical Example

The NEMS modules coinciding with the five primary sectors include rich technology detail. Multiple technology options modeled for many individual end uses, multiple levels of efficiency are available for each technology option, and improvements in the efficiency of individual technology options are modeled over the projection horizon. Also, new technologies often become available over the projection horizon. All of these technological improvements expand the potential for efficiency gains.

A key computation issue that arises in measuring aggregate efficiency is combining results across multiple technologies.[15] Focusing on the lighting example above (Example 2), there are several ways in which energy efficiency for lighting could be defined. The extremes are bounded by:

1. A measure of technological efficiency that aggregates the efficiency of each individual technology weighted by the energy consumption of that technology[16]
2. A measure of end-use efficiency that is constructed by first aggregating the lighting output and energy consumption from all lighting technologies and then calculating end-use efficiency as the ratio of total lumens provided to total energy consumption. This end-use oriented measure of efficiency includes technology switching as a source of efficiency change.

The former measure requires data by technology; the latter measure does not, because lighting is treated as a single composite technology. The appropriateness of each measure depends on the goals and uses for the measure. Technological efficiency is a narrow definition of efficiency that counts only efficiency changes that occur in specific technologies. Under this measure, if individual technology efficiencies were static, then a switch from incandescent lighting to fluorescent lighting would not result in any measured efficiency gain. The end-use oriented measure is more broadly defined, and a successful program that resulted in the replacement of incandescent lighting with fluorescent lighting would result in a measured efficiency gain.

To make the differences between these two definitions more concrete, consider the following hypothetical lighting example. The base period is the reference period against which an efficiency change is to be measured. Assume there are only two types of lighting, incandescent and fluorescent, and that between the base period and the current period there is a shift from fluorescent to incandescent lighting. The shaded entries in the table below represent the assumptions for this example; the other entries are calculations, totals, and weighted averages.

[13] This ratio includes both conversion losses and transmission and distribution losses. Conversion losses reflect the fact that converting a fuel to electricity requires more energy input than the Btu content of the electricity produced. Transmission and distribution losses stem from transformer inefficiencies as voltage is stepped-up for transmission and down for end uses, as well as from resistance in electric lines as the electricity is transmitted from the generation site to the end-use site.

[14] There are a variety of ways to measure energy intensity for the residential sector. If it is measured on a per household basis, then energy intensity will increase as housing size increases (all else being equal), as hypothesized in the example. If it is measured on a floorspace area basis, energy intensity will be unchanged in the example. If it is measured per unit of real GDP, the change in energy intensity will depend on the growth rate of real GDP relative to that of floorspace area.

[15] In general, the technologies do not have to service only a single end use; however, within a defined end use, the output measures will all be in the same terms, making the concept less complicated.

[16] The relevant weights for aggregating technologies into an efficiency index are energy consumption shares by technology. The weights and weighting procedures are discussed below.

Sample Lighting Data

	Lumens Provided	Efficiency (Lumens per Watt)	Energy Consumption (Watts)
Base Period:			
Incandescent	375	15.0	25.0
Fluorescent	1,500	60.0	25.0
Totals	1,875	37.5	50.0
Current Period:			
Incandescent	750	15.5	48.4
Fluorescent	1,125	75.0	15.0
Totals	1,875	29.6	63.4

Assume that there is a shift toward incandescent lighting in the current period, and that the lumens from fluorescent lighting are reduced by the amount that incandescent lighting is increased, leaving total lighting services unchanged. Also, assume that between periods both technologies improve in efficiency, but that fluorescent technology increases the most in percentage terms.

Now assume that individual technologies are not observed, and that lighting efficiency is measured by aggregate lumens per watt as follows:

Aggregate End Use Indexing Procedure

	Lumens Provided	Efficiency (Lumens per Watt)	Energy Consumption (Watts)
Total Lighting:			
Base Period	1,875	37.5	50.0
Current Period	1,875	29.6	63.4

Efficiency Change from Base Period = -21%

The measured efficiency change based on aggregate lumens per watt is a 21-percent decrease—even though the efficiencies of the underlying technologies all increase. This decrease is the direct result of the shift to the less efficient incandescent lighting and the assumption that the services provided by the different lighting types are the same.

An alternative calculation is to measure efficiency changes for each technology and aggregate them. Two indexing procedures are presented. The first is a Laspeyres Index, which is the same procedure used for certain components of the consumer price index (CPI). The CPI is determined by calculating how much a base year "market basket" of goods would cost at current period prices. The CPI index value is the ratio of the market basket cost at current prices to the base year cost. If lumens are viewed as the quantity and efficiency as the price, then energy consumption is the parallel concept of cost or expenditure on the market basket, and efficiency is parallel to inflation.

Technology-Based Laspeyres Indexing Procedure

	Base Period Lumens Provided	Current Period Efficiency (Lumens per Watt)	Estimated Energy Consumption at Current Efficiency (Watts)
Incandescent	375	15.5	24.2
Fluorescent	1,500	75.0	20.0
Indexed Energy Consumption			44.2

Efficiency Difference Between Periods = 13.1%
[(Base Consumption / Indexed Consumption at Current Period Efficiency) - 1]

Recall from the lighting data assumptions that incandescent lighting was assumed to increase in efficiency by 3 percent, while fluorescent lighting was assumed to increase by 25 percent. The efficiencies of both technologies are increasing, and intuitively the composite efficiency change should lie between 3 and 25 percent. The calculations are consistent with this intuition. Using base period quantities (lumens) and current period efficiencies results in a calculated consumption index of 44.2 watts, a decrease from the base period actual usage of 50 watts, which translates into a 13.1-percent increase in efficiency for the current period relative to the base period by the Laspeyres Index method [13.1% = (50.0 / 44.2) - 1].

The use of base period lumens was an arbitrary choice in the Laspeyres methodology; another equally valid procedure would be to use current period weights at base period efficiencies and to compare the resulting energy consumption index to current period consumption. This is known as the Paasche Index. In the current period, the energy consumption weight for incandescent lighting is 50 watts, compared with 24.2 watts in the Laspeyres method. At the same time, the weight for fluorescent lighting is 18.8 watts, compared with 20 watts using the Laspeyres method. Thus, the emphasis under the Paasche procedure shifts to the technology gaining the least in efficiency. Intuitively, the composite efficiency change should be less for the Paasche Index than for the previous example, and this is verified by the calculation [8.5% = (68.8 / 63.4) - 1].

Technology-Based Paasche Indexing Procedure

	Current Period Lumens Provided	Base Period Efficiency (Lumens per Watt)	Estimated Energy Consumption at Base Period Efficiency (Watts)
Incandescent	750	15.0	50.0
Fluorescent	1,125	60.0	18.8
Indexed Energy Consumption			68.8

Efficiency Difference Between Periods = 8.5%
[(Indexed Consumption at Base Period Efficiency / Current Consumption) - 1]

Two additional indexing procedures illustrate the motivation for the choice of the indexing procedure chosen for the ACEI that will be described in detail later. The two examples above rely on the arbitrary choice of a base period. This arbitrary choice affects the results in both cases. The Fischer Index removes that arbitrariness by taking the average of the two results (computed as the geometric mean of the Laspeyres and Paasche Indexes). Thus, its calculation does not depend on the arbitrary choice of a base period. As an average, its results are between those of the Laspeyres and Paasche methods.

Technology-Based Fischer Indexing Procedure

	Efficiency Difference Between Periods (Percent)
Laspeyres Indexing Procedure	13.1
Paasche Indexing Procedure	8.5

Efficiency Difference Between Periods = 10.8%
(Geometric Mean of Laspeyres and Paasche Results)

The other indexing procedure is called the Törnqvist Index formula. It too is invariant to the choice of the base period. Furthermore, its results are often for practical purposes indistinguishable from the Fischer Index.[17] It has been widely used in energy analysis and was chosen as the basis for calculating the ACEI. A description of its computation methodology is provided in the Appendix.

The principal result illustrated by this extended example is that the level of measurement (in this case either individual technologies or the end use as a whole) can make a striking difference in the results. The technology-based indexes are appropriate for estimating changes in specific technologies; the aggregate end-use level calculation is appropriate for measuring the efficiency of specific end-use services. The calculation of the ACEI measures the efficiencies of the various end uses of energy in the economy, not of individual technologies. This is the broader definition from the example and will attribute shifts among competing technologies with different energy efficiencies within an end use to changes in energy efficiency. The exact specification of what constitutes an end use is often arguable, and a further example based on *AEO2002* projections for LDVs in the transportation sector is provided in the discussion of Figure 3 below to illustrate the issues.

A second observation from the above example is that the indexing methodology can also make an important difference, as illustrated by the different estimates for the Laspeyres, Paasche, and Fischer Indexes. Once the end-use sectors have been defined, the choice of a weighting scheme for calculations based on projections for the U.S. economy is less significant than it is in the constructed example above. The energy weights in the U.S. economy are more stable than in the example, because nearly all the energy consumption in the economy is attributable to long-lived durable goods or capital goods, which imparts considerable stability to the weights.

Subsector Detail

NEMS models energy consumption as the aggregation of sectoral energy demands, with each sector comprising various subsector components (e.g., vehicle types within a class, housing types, industrial processes and output classifications, or end uses). Table 1 lists the subsector detail used for the indexing procedure. For the residential and commercial sectors, subsectors are defined for each end use and fuel combination by Census Division and building type. This leads to a large number of subsectors, but the amount of computational detail is appropriate. Different building types in different areas of the country have considerably different inherent energy requirements for space heating and cooling. Treating the various combinations of end use, building type, and Census Division as separate subsectors will not inappropriately attribute shifts in geographic distribution or shifts in housing types or commercial activity to changes in efficiency. In the transportation sector, subsectors are defined for each major vehicle category or transportation mode. In the industrial sector, subsectors are defined as entire industries. For electricity generation, no subsector detail is required; efficiency is measured as the ratio of aggregate sales of kilowatthours (as indicated on customers' electric meters) to Btu input. This is based on the concept that the output, kilowatthours of sales, provides an essentially homogeneous energy service regardless of how it was generated, and therefore any improvements in the ratio of kilowatthours of sales to Btu input should be counted as efficiency gains.

Calculating the Inverse of Energy Efficiency

The efficiency calculations include an economy-wide ACEI along with its component sectoral indexes. These indexes are presented in terms of the inverse of energy efficiency, that is, energy consumption per unit of service demand.[18] This ratio develops inverse efficiency estimates (smaller index values are associated with higher levels of efficiency). By calculating the inverse, the aggregate composite efficiency measure is directly comparable to the energy to real GDP ratio.

[17] Results for the Törnqvist Index also produce an estimated efficiency change of 10.8 percent.

[18] A service demand proxy is used when a direct indicator of service demand is not available. An example in the transportation sector is that there is no readily available service demand indicator for lubricants. The proxy in this case is indicated in Table 1 under the 10th subsector under the Transportation Sector heading as Real Gross Domestic Product.

Constructing Subsector-Specific Efficiency Indexes

While NEMS results reflect the effects of efficiency changes for a rich characterization of technologies, efficiency indexes are generally not tracked in the accounting frameworks at the level of detail desired for this analysis. For example, in the case of the buildings modules, energy efficiencies are incorporated at the equipment and technology level but are not reported at the end use and fuel level, which is the working definition of a subsector for the buildings modules as listed in Table 1. The effects of efficiency changes are reflected in the end-use results, as are several other factors such as weather, price elasticities, housing unit size, and service demand penetration.

For calculating efficiency, factors other than efficiency that affect end-use consumption must be removed, so that adjusted energy consumption on a unitized basis (e.g., energy consumption per square foot) becomes a measure of end-use efficiency. That is, once all the factors unrelated to efficiency are removed, the adjusted energy consumption per household or per square foot embodies only the effects of changed efficiency. Table 1 includes the subsector energy service measure or proxy. For buildings, the proxy is energy consumption per square foot for the specific end use, after the effects of weather, price elasticity, and new service demand penetration have been removed.

Using residential space heating as an example, adjusted natural gas energy consumption per gas-heated household (i.e., conditional household) equates to the inverse of efficiency. After adjusting for housing unit size, households become a more direct proxy for service demand, and the adjusted energy consumption reflects the “efficiency-related” amount of energy required to meet that service demand.

For the NEMS buildings models, the following adjustments are made to the end-use energy consumption before the end-use efficiency indicators are calculated:

- For end uses such as residential air conditioning and commercial personal computer office equipment, energy consumption caused by increasing service demand penetration is removed to the extent possible before calculating energy efficiency.
- For residential televisions, adjustments are made for the increased energy consumption of the increasingly popular larger screen sizes, because they provide enhanced energy services.
- For residential housing, the effects of increasing size of housing units are removed before the efficiency indicator is computed. This is equivalent to using residential square footage covered by an end-use as a proxy for service demand. Commercial energy consumption is already modeled on a per square foot basis.
- Adjustments are made for conservation and short-run elasticity effects, including efficiency rebound and weather effects.

For the transportation sector, direct efficiency estimates are available for all end uses except pipeline fuel and lubricants. The direct efficiency estimates are framed in terms of either fleet average miles per gallon or ton-miles shipped per gallon. The estimates of service demand—such as vehicle-miles traveled, seat-miles available, and ton-miles shipped—are used directly in the efficiency calculations for the ACEI. All that needs to be done is to compute inverse values for the ACEI. For the two subsectors without efficiency measures, pipeline fuel and lubricants, energy intensities based on real GDP are used as proxies for efficiency.

For the industrial model, the 13 subsectors have direct measures of service demand in the real output measures for the subsectors. Inverse efficiency indicators are computed as energy consumption per unit of real output for each of these subsectors. Unlike the treatment of price effects in the buildings sector, where price changes lead to short-run elasticity effects that are classified as conservation, industrial production responds to price changes by substituting one input for another. For example, if changing energy prices cause a substitution between capital and fuel input or labor and fuel input, then the effects are appropriately classified as energy efficiency changes instead of conservation.

For electricity generation, the output measure is electricity sales to end users. The inverse efficiency is calculated as energy consumption (including conversion losses and transmission and distribution losses) per unit of sales. Changes in energy efficiency can result from more efficient generating technologies or from reductions in transmission and distribution losses.

Table 1. Definitions of Sectors and Subsectors for the Energy Efficiency Calculations

	Fuel and End Use	Energy Service Measure		Fuel and End Use	Energy Service Measure
Residential Sector (Dimensionality = 29 Subsectors, 9 Census Divisions, 3 Housing Types)			**Commercial Sector (Dimensionality = 21 Subsectors, 9 Census Divisions, 11 Building Types)**		
Electricity			***Purchased Electricity***		
1	Space Heating	Conditional Floorspace Area	1	Space Heating	Conditional Floorspace Area
2	Space Cooling	Conditional Floorspace Area	2	Space Cooling	Conditional Floorspace Area
3	Water Heating	Conditional Floorspace Area	3	Water Heating	Conditional Floorspace Area
4	Refrigeration	Conditional Floorspace Area	4	Ventilation	Conditional Floorspace Area
5	Cooking	Conditional Floorspace Area	5	Cooking	Conditional Floorspace Area
6	Clothes Dryers	Conditional Floorspace Area	6	Lighting	Conditional Floorspace Area
7	Freezers	Conditional Floorspace Area	7	Refrigeration	Conditional Floorspace Area
8	Lighting	Total Floorspace Area	8	Office Equipment (PC)	Conditional Floorspace Area
9	Clothes Washers	Conditional Floorspace Area	9	Office Equipment (non-PC)	Conditional Floorspace Area
10	Dishwashers	Conditional Floorspace Area	10	Other Uses	Conditional Floorspace Area
11	Color Televisions	Total Floorspace Area	***Natural Gas***		
12	Personal Computers	Total Floorspace Area	11	Space Heating	Conditional Floorspace Area
13	Furnace Fans	Conditional Floorspace Area	12	Space Cooling	Conditional Floorspace Area
14	Other Uses	Total Floorspace Area	13	Water Heating	Conditional Floorspace Area
Natural Gas			14	Cooking	Conditional Floorspace Area
15	Space Heating	Conditional Floorspace Area	15	Other Uses	Conditional Floorspace Area
16	Space Cooling	Conditional Floorspace Area	***Distillate Fuel***		
17	Water Heating	Conditional Floorspace Area	16	Space Heating	Conditional Floorspace Area
18	Cooking	Conditional Floorspace Area	17	Water Heating	Conditional Floorspace Area
19	Clothes Dryers	Conditional Floorspace Area	18	Other Uses	Conditional Floorspace Area
20	Other Uses	Total Floorspace Area	***Other Fuels***		
Distillate Fuel			19	—	Total Floorspace Area
21	Space Heating	Conditional Floorspace Area	***Renewables***		
22	Water Heating	Conditional Floorspace Area	20	—	Total Floorspace Area
23	Other Uses	Total Floorspace Area	***Biomass***		
Liquefied Petroleum Gas			21	—	Total Floorspace Area
24	Space Heating	Conditional Floorspace Area			
25	Water Heating	Conditional Floorspace Area			
26	Cooking	Conditional Floorspace Area			
27	Other Uses	Total Floorspace Area			
Marketed Renewables (Wood)					
28	Space Heating	Total Floorspace Area			
Other Fuels					
29	—	Total Floorspace Area			

	Subsector	Energy Service Measure		Subsector	Energy Service Measure
Industrial Sector (Dimensionality = 13 Subsectors)			**Transportation Sector (Dimensionality = 10 Subsectors)**		
1	Refining	Refining Real Output	1	Light-Duty Cars	Vehicle-Miles Traveled
2	Food Industry	Food Industry Real Output	2	Light-Duty Trucks	Vehicle-Miles Traveled
3	Paper Industry	Paper Industry Real Output	3	Motorcycles	Vehicle-Miles Traveled
4	Bulk Chemicals	Bulk Chemicals Real Output	4	Commercial Light Trucks	Vehicle-Miles Traveled
5	Glass Industry	Glass Industry Real Output	5	Freight Trucks	Vehicle-Miles Traveled
6	Cement	Cement Real Output	6	Air	Seat-Miles Available
7	Iron and Steel	Iron and Steel Real Output	7	Rail	Ton-Miles Traveled
8	Aluminum	Aluminum Real Output	8	Marine	Ton-Miles Traveled
9	Agriculture	Agriculture Real Output	9	Pipeline Fuel	Real Gross Domestic Product
10	Construction	Construction Real Output	10	Lubricants	Real Gross Domestic Product
11	Mining	Mining Real Output			
12	Metal-Based Durables	Metal-Based Durables Real Output	**Electricity Generation Sector (Dimensionality = 1 Subsector)**		
13	Other Manufacturing	Other Manufacturing Real Output		All Electricity Supply	Sales (Billion Kilowatthours)

Source: Energy information Administration, Office of Integrated Analysis and Forecasting.

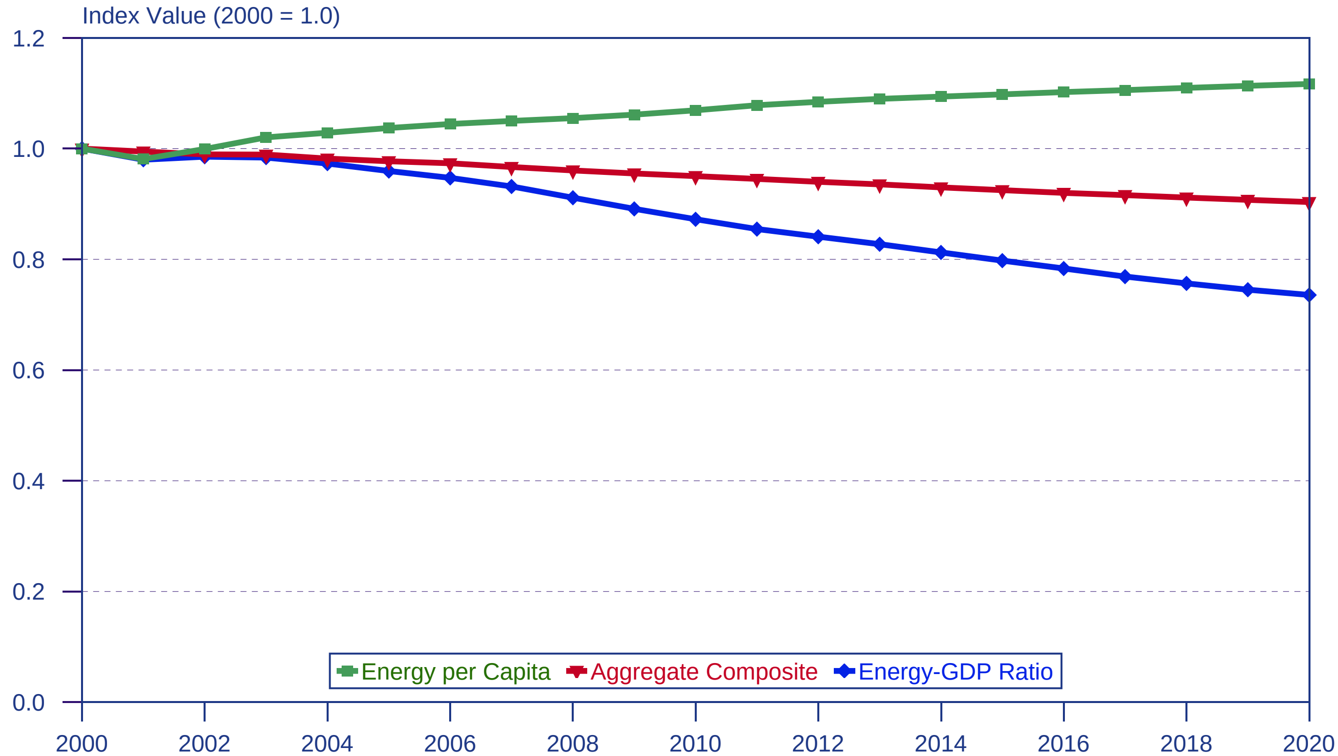
AEO2002 Results

Reference Case

Figure 1 compares the ACEI and two commonly used, economy-wide intensity measures. All indexes use a base year of 2000. Note that energy consumption on a per capita basis rises throughout the projection interval, while the energy-to-real GDP ratio and the ACEI show intensity decreases or efficiency increases by their declines. The average rate of decline for the ratio of energy consumption to real GDP is approximately triple that for the ACEI, reflecting other shifts in the economy beyond efficiency improvements.

To sharpen the comparisons, Table 2 provides 5-year growth rates for the indexes illustrated in Figure 1. The ratio of energy to real GDP falls more slowly in the first 5-year interval, with annual rates in the other intervals close to double that of the first interval. Energy use per capita increases most rapidly in the first interval, with average annual growth rates slowing in each successive period. The ACEI exhibits a somewhat more uniform pattern, with similar rates of decline in the first and last intervals and slightly higher rates in the middle intervals. One additional observation from Table 2 is that, although the ACEI never declines as rapidly as the ratio of energy to real GDP, in the first interval its average rate of decline is just over one-half that of the energy-GDP

Figure 1. Changes in the Aggregate Composite Efficiency Index (ACEI) Compared With Changes in Energy Intensity Measures, *AEO2002* Reference Case, 2000-2020



Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

Table 2. Changes in the Aggregate Composite Efficiency Index (ACEI) Compared With Changes in Energy Intensity Measures by 5-Year Intervals, *AEO2002* Reference Case, 2000-2020

Measure	2000-2005	2005-2010	2010-2015	2015-2020	2000-2020
Average Annual Growth Rates Over 5-Year Intervals (Percent)					
Energy to Real GDP Intensity . .	-0.82	-1.89	-1.77	-1.61	-1.52
Energy per Capita Intensity	0.73	0.61	0.53	0.34	0.55
ACEI.	-0.46	-0.56	-0.54	-0.47	-0.51
Ratio of 5-Year Growth Rates of Activity Indicators to Real GDP					
Energy per Capita Intensity	-0.89	-0.32	-0.30	-0.21	-0.36
ACEI.	0.56	0.29	0.30	0.29	0.33

Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

ratio. In the subsequent intervals, its average rate of decline is less than one-third that of the energy-GDP ratio. For the entire 2000 to 2020 interval, the rate of decline in the ACEI is almost exactly one-third that of the energy-GDP ratio, indicating that most of the decline in the energy-GDP ratio is "structural" in nature.

The relationship between the ratio of energy consumption to real GDP and the ACEI can be better understood by comparing growth rates of sectoral activity indicators with real GDP. Table 3 compares projected growth rates for 5-year intervals and provides ratios of the sectoral indicator growth rates to the growth of real GDP. While all indicators except LDV miles traveled in the first interval grow more slowly than does real GDP, their growth relative to real GDP is higher in the first interval than in the other intervals in all cases. Because many of these activity indicators are used in the construction of the ACEI, the ACEI should decline at a rate closer to the rate of decline in the energy-GDP ratio in the first interval, as verified in Table 2.

The projections also exhibit a fairly uniform tapering off of activity and output growth rates for most indicators, reflecting economy-wide macroeconomic and demographic effects. Also, for most of the 5-year intervals, the fastest growing measures are real GDP and real industrial gross output.

To illustrate the effects of the projected changes in the three indexes over the forecast period, Figure 2 compares the reference case projections of U.S. energy consumption with alternative projections derived by holding each of the indexes at its 2000 value. In the reference case, energy consumption is projected to increase at an average annual rate of 1.4 percent. If energy consumption per capita had remained constant, the reference case growth rate would have been reduced to 0.8 percent per year. In contrast, if there had been no improvement in the energy intensity of the economy, or if energy efficiency had not increased, energy consumption would have grown more rapidly than projected in the reference case.

Assuming no change in the ACEI from its 2000 value, energy consumption in 2020 is projected to be 145 quadrillion Btu, or 14 quadrillion Btu higher than the reference case projection of 131 quadrillion Btu. Assuming no change in the ratio of energy use to real GDP, energy consumption in 2020 is projected to be 178 quadrillion Btu, or 47 quadrillion Btu higher than the reference case projection.

Figure 3 builds on the information described in Example 1 above to provide a more concrete illustration of how the definition of a subsector can affect the results. In Example 1, the trend away from passenger cars toward light trucks was described. This trend is projected to continue in *AEO2002*. LDV miles per gallon increases on average by 0.3 percent per year over the projection interval. In the forecast, both passenger car miles per gallon and light truck miles per gallon increase over the projection period, averaging 0.3 percent and 0.7 percent, respectively. As discussed in Example 1, it is assumed here that light trucks provided a different quality or type of service than passenger cars, suggesting that a single LDV category is too broad, and that the average annual growth rate for LDV efficiency of 0.5 percent is a more appropriate calculation.

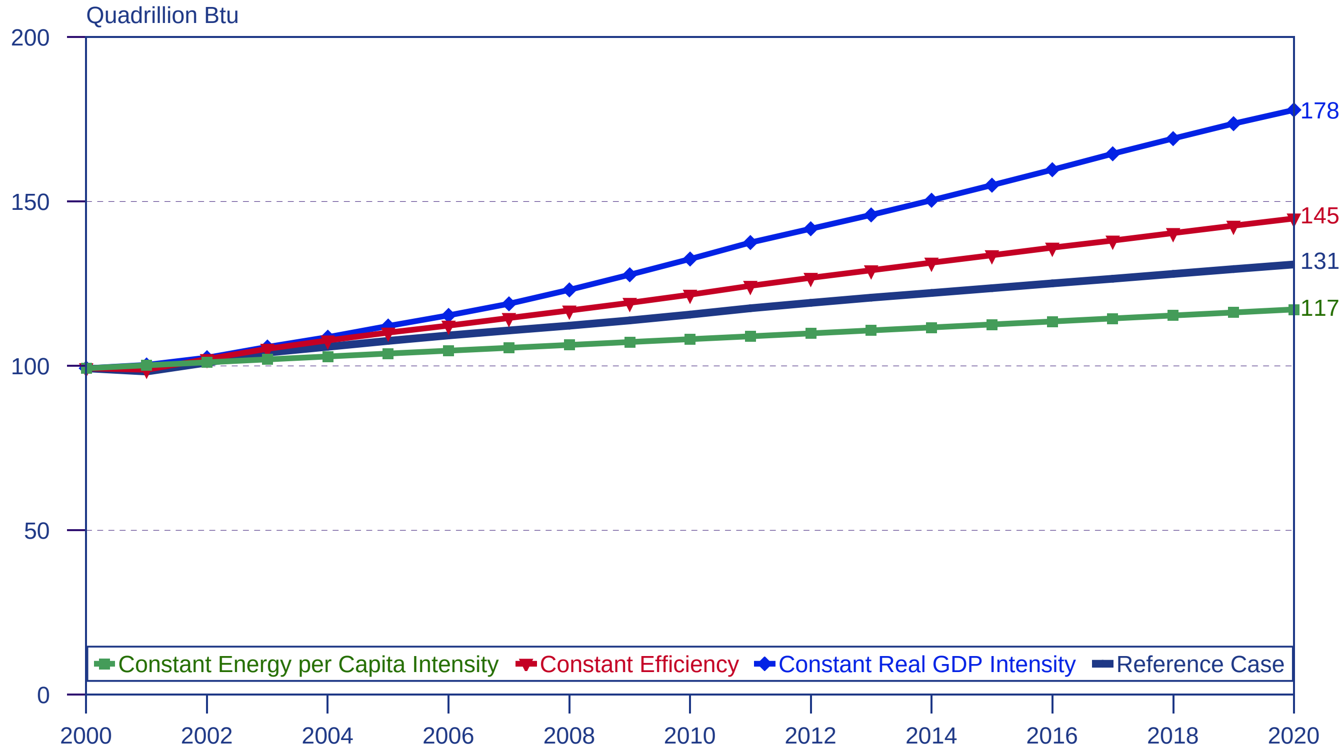
Figure 3 shows two alternative versions of the transportation sector index. One, the "Accounting for Light-Duty

Table 3. Changes in Activity and Output Measures by 5-Year Intervals, *AEO2002* Reference Case, 2000-2020

Measure	2000-2005	2005-2010	2010-2015	2015-2020	2000-2020
Average Annual Growth Rates Over 5-Year Intervals (Percent)					
Real GDP	2.47	3.40	3.18	2.79	2.96
Population	0.88	0.83	0.81	0.80	0.83
Number of Households	0.98	0.99	0.93	0.92	0.95
Commercial Floorspace	2.13	1.59	1.55	1.35	1.66
Light-Duty Vehicle Miles Traveled	2.59	2.31	2.16	1.82	2.22
Total Industrial Gross Output	2.32	3.01	2.73	2.31	2.59
Electricity Sales	2.05	1.91	1.79	1.53	1.82
Ratio of 5-Year Growth Rates of Activity Indicators to Real GDP					
Population	0.36	0.24	0.26	0.29	0.28
Number of Households	0.40	0.29	0.29	0.33	0.32
Commercial Floorspace	0.87	0.47	0.49	0.48	0.56
Light-Duty Vehicle Miles Traveled	1.05	0.68	0.68	0.65	0.75
Total Industrial Gross Output	0.94	0.89	0.86	0.83	0.88
Electricity Sales	0.83	0.56	0.56	0.55	0.62

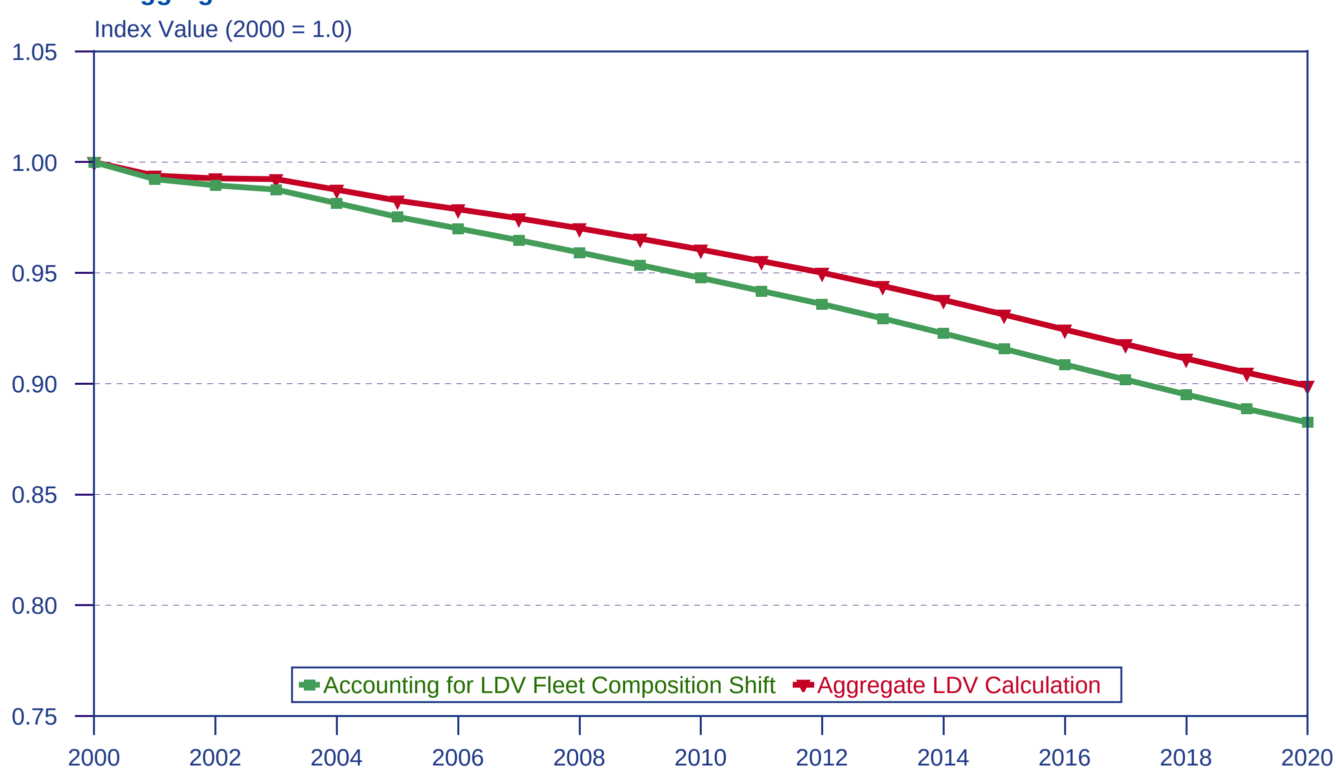
Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

Figure 2. Projections of Primary Energy Consumption, *AEO2002* Reference Case, and Estimates Holding Energy Intensity and Efficiency at Base-Year Levels, 2000-2020



Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

Figure 3. Alternative Calculations of Transportation Energy Efficiency, *AEO2002* Reference Case, 2000-2020: Accounting for Light-Duty Vehicle (LDV) Fleet Composition Shift Versus Aggregate LDV Calculations



Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

Vehicle Composition Shift," includes subcategories of cars, light trucks, and motorcycles in the LDV component. This is the breakout of the transportation sector that was used in the construction of the ACEI. The other index, the "Aggregated Light Duty Vehicle Calculation," is constructed using only aggregate miles per gallon for the combined LDV fleet, likely the more familiar calculation to most readers, as it tends to be more widely reported. This method reflects the composition shift to light trucks as a factor that decreases aggregate fleet miles per gallon and thus offsets some of the efficiency increases. The expected result is borne out in Figure 3, where the index that treats the entire LDV fleet as an aggregate service category declines at an average rate of 0.5 percent per year. In contrast, the transportation efficiency index component of the ACEI exhibits a greater efficiency gain, declining at an average rate of 0.6 percent per year.

Another comparison of interest is the difference between estimated industrial efficiency for the ACEI and aggregate industrial intensity based on total industrial energy use per unit of real industrial output. The latter ratio declines on average by 1.4 percent annually between 2000 and 2020. Industrial efficiency also declines (improves) but at approximately one-fourth the rate, or 0.3 percent annually. This result is consistent with the recent and projected continuing shift toward an industrial output mix weighted toward less energy-intensive industries. In Figure 4, the difference between the two indexes can be viewed as the structural component of the decline in energy use per unit of real output for the industrial sector.

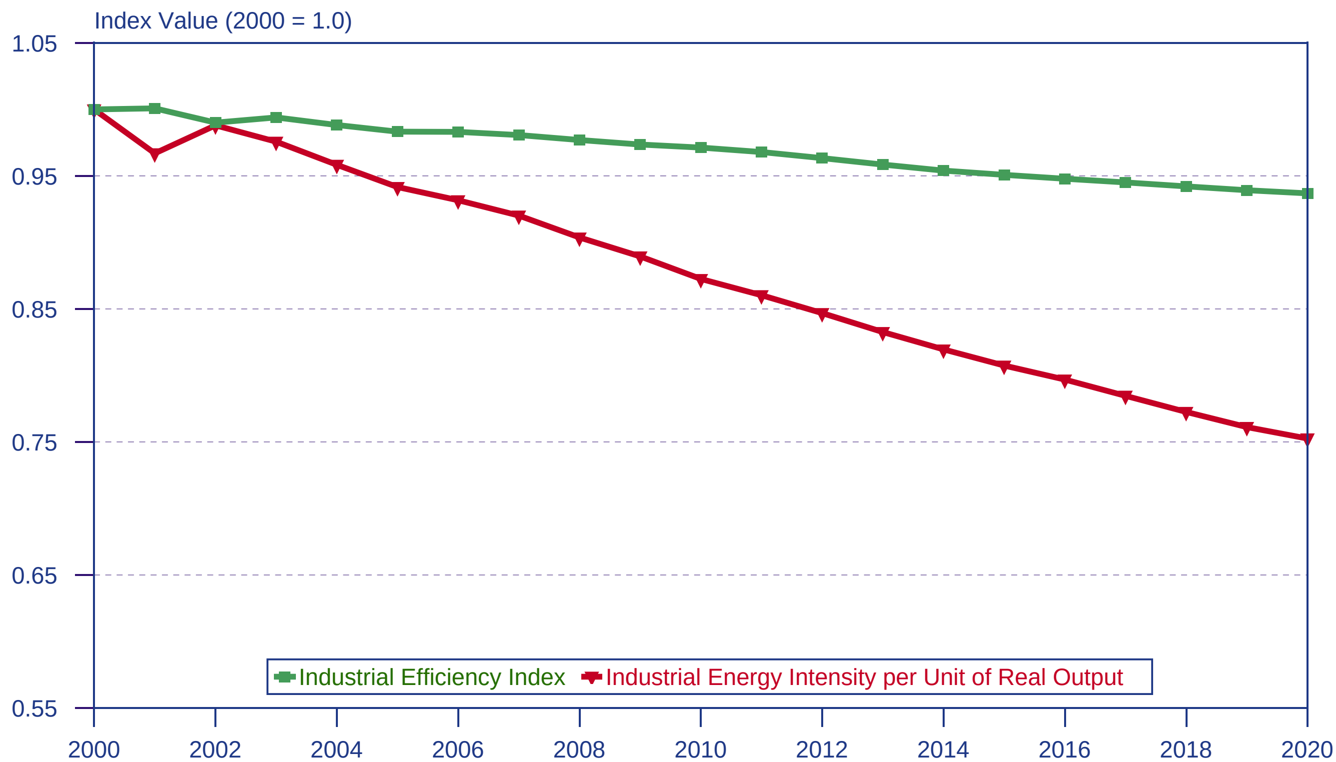
Figure 5 shows the ACEI results for each of the five end-use sectors. Note that, for most years, monotonic improvements in efficiency occur. In rank order, the electricity generation sector exhibits the greatest efficiency improvement by 2020, followed by the transportation, residential, commercial, and industrial demand sectors. Average annual growth rates for the five sectors are shown in the legend of Figure 5.

Table 4 shows the sectoral components of the ACEI for selected years and illustrates the Törnqvist Index weighting procedure. The first panel of the table shows growth rates (logarithmic) for the individual sectoral indexes. The second panel shows weighted growth rates based on chained shares of total energy consumption for each sector (weights are not shown). Summation of the weighted sectoral growth rates yields the aggregate indexed energy intensity estimates.

Integrated Technology Cases

Two alternative cases were developed in support of the *AEO2002*, a high technology case and a 2002 technology

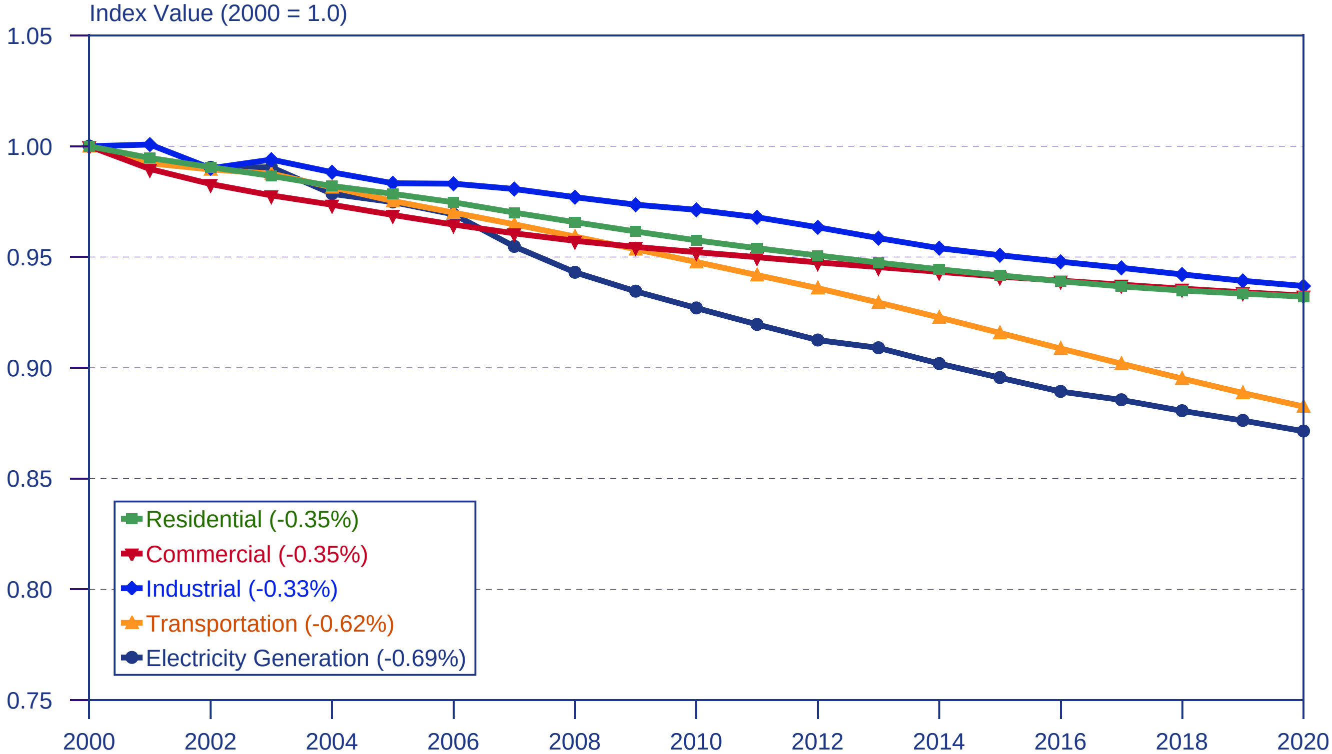
Figure 4. Changes in Industrial Energy Efficiency Measured by the Aggregate Composite Efficiency Index (ACEI) Compared With Changes in Industrial Energy Intensity per Unit of Real Output, *AEO2002* Reference Case, 2000-2020



Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

case. In the 2002 technology case, efficiencies are assumed to be fixed at 2002 levels with no further improvements in the years beyond. Note that even with a fixed menu of available technology efficiencies, improvements in end-use or process efficiency can occur as stock turnover occurs or when the mix of purchased efficiency levels changes. The high technology case generally advances the projected availability of efficiency improvements in the reference case, often at lower costs. Furthermore, advanced technologies not available in the reference case may be modeled, often with efficiency levels that exceed the maximums in the reference case.

Figure 5. Sectoral Changes in Energy Efficiency Measured by the Aggregate Composite Efficiency Index (ACEI), *AEO2002* Reference Case, 2000-2020



Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

Table 4. Changes in Energy Efficiency by Sector Measured by the Aggregate Composite Efficiency Index (ACEI) Compared With Energy Intensity Measures by 5-Year Intervals, *AEO2002* Reference Case, 2000-2020

Measure and Sector	2000-2005	2005-2010	2010-2015	2015-2020
Average Annual Growth Rates in Efficiency Indexes Over 5-Year Intervals (Percent)				
Residential	-0.36	-0.41	-0.29	-0.15
Commercial	-0.47	-0.25	-0.23	-0.16
Industrial	-0.50	-0.24	-0.33	-0.25
Transportation	-0.63	-0.61	-0.76	-0.69
Electricity Generation	-0.38	-0.81	-0.71	-0.55
Average Annual Growth Rates in Energy-Weighted Efficiency Indexes Over 5-Year Intervals (Percent)				
Residential	-0.04	-0.04	-0.03	-0.02
Commercial	-0.04	-0.02	-0.02	-0.01
Industrial	-0.14	-0.06	-0.09	-0.07
Transportation	-0.18	-0.18	-0.23	-0.21
Electricity Generation	-0.10	-0.20	-0.17	-0.13
ACEI	**-0.49**	**-0.51**	**-0.54**	**-0.44**
Energy to Real GDP Intensity	**-1.38**	**-2.11**	**-1.81**	**-1.28**
Energy per Capita Intensity	**0.83**	**0.74**	**0.37**	**0.30**

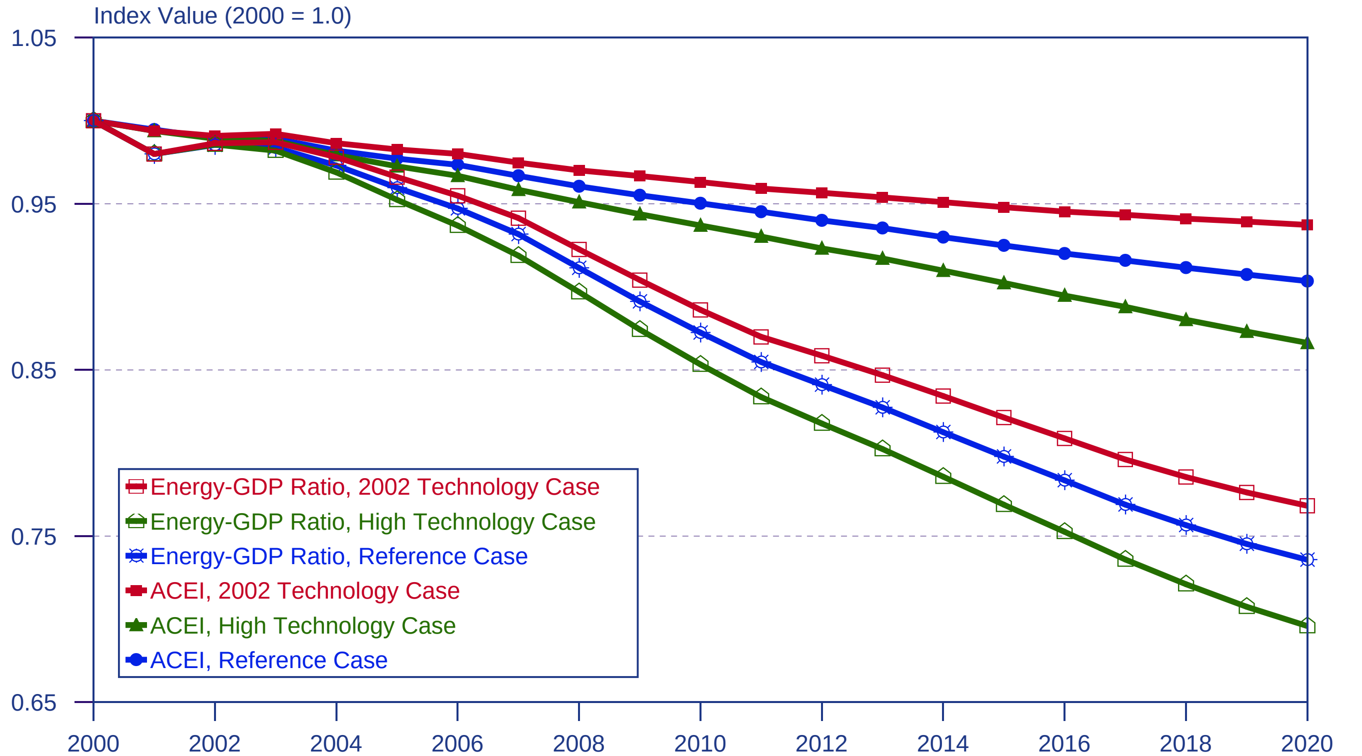
Source: Energy Information Administration, National Energy Modeling System run AEO2002.D102001B.

These two cases will have a direct effect on the projected efficiency indexes for the individual sectors, translating nearly one-for-one into changes in both the ratio of energy to real GDP and the ACEI, because the gaps between the technology cases are similar for the alternate measures. This result indicates that the changes made to the models for the efficiency cases largely translate into estimated efficiency changes, as would be expected, because the cases involve variation in equipment efficiency. Figure 6 illustrates the results for the alternative cases and the reference case.

Another way of analyzing the integrated technology cases is along the lines of the results portrayed in Figure 2. Recall that Figure 2 provided alternative energy projection paths based on assumptions of energy efficiency held fixed at its 2000 level, the energy to real GDP ratio held constant at its 2000 level, and energy per capita also fixed at its 2000 level. Table 5 presents the results for 2020 from Figure 2 and adds columns for the two technology cases.

In Table 5, the *AEO2002* projections in the first row vary from case to case due to the sensitivity of energy consumption to the varying technology assumptions across the cases. The Constant Efficiency projections exhibit less sensitivity, as expected, because if all the differences in energy consumption among the three cases were entirely the result of efficiency gains, then setting the efficiency to a constant level would merely “replace” or “remove” the altered energy consumption (relative to the reference case). The differences in the entries in

Figure 6. Changes in the Aggregate Composite Efficiency Index (ACEI) Compared With Changes in Energy Intensity Measures, *AEO2002* Reference, 2020 Technology, and High Technology Cases, 2000-2020



Source: Energy Information Administration, National Energy Modeling System runs AEO2002.D102001B, LTRKITEN.D102501A, and HTRKITEN.D102501A.

Table 5. Projections of Primary Energy Consumption in 2020 in *AEO2002* Cases Assuming Constant Energy Efficiency and Intensity Measures at 2000 Levels
(Quadrillion Btu)

Assumption	Reference Case	2002 Technology Case	High Technology Case
AEO2002	131	137	123
Constant Efficiency.	145	146	143
Constant Energy-GDP Ratio	178	178	177
Constant Energy per Capita	117	117	117

Source: Energy Information Administration, National Energy Modeling System.

Table 5 result from non-efficiency structural changes in the cases. These structural changes arise from differential changes in energy service demands among the end-use sectors. For example light-duty vehicle miles traveled increase by 0.7 percent in 2020 over the reference case in the high technology case and fall by 0.4 percent in the 2002 technology case. On the other hand, residential housing stocks are unaffected across the cases. Results like these lead to compositional effects that cause the Constant Efficiency results to vary slightly across the cases. The Constant Energy-GDP Ratio entries and the Constant Energy per Capita entries exhibit little change, because real GDP is only slightly affected by technology assumptions, and the population estimates are exogenous and thus invariant to technology assumptions.

Summary

There is a significant difference between the ratio energy use to real GDP and the ACEI over the projection horizon, which can be attributed primarily to structural changes in the economy that are included in the energy-GDP ratio but are removed by the more detailed efficiency calculations. Part of the structural change results from the formulation of sectoral efficiency indexes in terms of sector-specific service demand indicators, instead of using the relatively rapidly growing real GDP as a proxy for economy-wide service demand. In addition to sector-specific drivers, the aggregate indexed intensity presented here removes several other factors unrelated to long-term changes in the way energy is used at the subsector level, including the effects of:

- Weather on building sector energy intensity
- Changes in the geographical distribution of buildings over time
- Changes in the composition of building types, reflecting economic and demographic trends in buildings (i.e., mix changes in the composition of the 11 commercial building types or the 3 residential types characterized in NEMS)
- Service demand growth driven by the penetration of building end uses or the effects of changes in average housing unit size on residential energy intensity
- Short-run price responses to changes in energy prices (elasticity effects)
- Varying growth rates in the output of individual industrial subsectors
- Any shifts in the mix of transportation modes.

The computed ACEI characterizes efficiency gains in the various end uses and subsector categories of NEMS. This indicator better isolates the effects on energy consumption that result from the adoption of more energy-efficient technologies than does the often-cited energy-GDP ratio. The sectoral components of the ACEI are also provided, in order to show the projected relative contributions to overall efficiency gains. However, because more detailed estimates are systematically available in NEMS than for actual data, historical estimates of energy efficiency often suffer from data limitations. Thus, the ratio of energy use to real GDP remains useful for long-term historical analysis and for international comparisons, where data gaps are often more severe than for the U.S. economy.

The ACEI is computed from a single-stage Törnqvist index of the U.S. economy by directly aggregating details for approximately 2,500 subsectors. Sectoral efficiency indexes are also calculated by aggregating only the details relevant to the five broad sectors. A comparison of a two-stage estimate with the single-stage ACEI indicates agreement to five significant digits. Additional layers of subsector detail could be constructed for some of the sectors, primarily the buildings sectors, principally for illustrating the effects of changes in the mix of building types and/or shifts in their distribution across the Census Divisions. Their construction would involve additional intermediate aggregations of the approximately 2,500 subsectors. Multi-stage indexes could also be constructed as part of the layering process.

An extension of the methodology to carbon dioxide emissions would also be possible. Conceptually, this extension of the methodology would provide measures of projected “carbon efficiency.” The concept would be developed on the basis of the ratio of carbon dioxide input per unit of service demand. Implementation of such an index will require capturing some of the subsector estimates at finer levels of detail than are required for the ACEI, in order to include energy use by fuel type in addition to total energy consumption.

Appendix
Details of the Indexing Procedure

Index numbers are often used to estimate aggregate concepts composed of diverse inputs. The index likely to be most familiar to people in the United States is the CPI. The CPI summarizes price increases for more than 200 representative goods and services into a single number, a "market basket" approach. Two common uses of the CPI are as an estimate of inflation in the U.S. economy and as a deflator to convert income or expenditure data into real quantities. The market basket approach uses purchases in a base period to develop the weights that apply to the various goods and services in the index. One criticism of an index like the CPI is that, as time passes, the composition of current purchases of consumers are represented less accurately by the base period market basket. Since updating the mix of goods in a typical market basket requires costly surveys of consumer purchases, it is typically done only once every 2 years.[19] For indexing in the NEMS modeling environment, annual updates to the mix of subsector activity are readily available in the model accounting framework.

For developing the ACEI, the annual accounting framework of NEMS provides a rich data set upon which to base the calculations. The Törnqvist index (also referred to as the Discrete Divisia index) was chosen. This index uses average weights between the two years being measured, which are referred to as rolling weights or chain weights. The "market basket" of energy-consuming subsector activity levels is updated annually within NEMS, thus adjusting for changes in composition over time. In addition to the adaptive weights, the Törnqvist Index has other desirable index properties and has been widely used, especially in productivity studies.[20]

The specific calculation for the aggregate composite efficiency index based on the Törnqvist Index formula is as follows:

$$ACEI_t = ACEI_{t-1} \exp\left[\sum_{i=1}^{N}\sum_{j=1}^{n(i)} W_{i,j,t}\ \ln\left(\frac{I_{i,j,t}}{I_{i,j,t-1}}\right)\right] \qquad (1)$$

where:

- $w_{i,j,t} = \left[0.5\left(\frac{e_{i,j,t}}{\sum_i\sum_j e_{i,j,t}} + \frac{e_{i,j,t-1}}{\sum_i\sum_j e_{i,j,t-1}}\right)\right]$ are the weights in year t for the jth subsector in the ith sector, defined as the average of the current year and prior year shares of total primary energy consumption;
- $ACEI_t$ is the aggregate composite (inverse) efficiency index in year t;
- N is the number of sectors (residential, commercial, industrial, transportation, and electricity generation);
- $n(i)$ is the number of subsectors for the particular sector;[21]
- $e_{i,j,t}$ represents total energy consumption for sector i, subsector j in year t with no adjustments for penetration, etc. (see adjustments discussion below); and
- $I_{i,j,t}$ represents the inverse efficiency index for sector i, subsector j in year t.

The definition and construction of these indexes for each sector are described in the next section.

Equation (1) defines the construction of a "single-stage" aggregate measure for the economy across all sectors. Individual sector indexes can also be constructed by eliminating the summation across sectors (the i subscript is changed to a superscript to denote concepts for the ith sector, but with no summation) as follows:

[19] The current schedule for updating the expenditure weights for the CPI is every 2 years, introduced into the index with a lag. The weights are 2 years old when introduced and 4 years old when retired. Previous updates were less frequent. See U.S. Department of Labor, Bureau of Labor Statistics, "Future Schedule for Expenditure Weight Updates in the Consumer Price Index," web site http://stats.bls.gov/cpi/cpiupdt.htm (December 18, 1998).

[20] The Törnqvist Index uses the average of base period and current period weights applied to percentage changes computed logarithmically. For more information on its properties, see W.E. Diewert, "Exact and Superlative Index Numbers," *Journal of Econometrics*, Vol. 4 (1976), pp. 115-145; and B.M. Balk and W. E. Diewert, "A Characterization of the Törnqvist Price Index," Discussion Paper No. 00-16, The University of British Columbia (October 2000). Ang and Liu have recently proposed a modification of this formula that adjusts the calculation of the weights (Log-Mean Divisia Index Method I); however, the differences in the calculations are insignificant when applied to the *AEO2002* projections. The results of a partial test indicate agreement in the index values to at least 5 significant digits, and results are presented to only 3 digits. For further details, see B.W. Ang and X.Q. Liu, "A New Energy Decomposition Method: Perfect in Decomposition and Consistent in Aggregation," *Energy*, Vol. 26 (2001), pp. 537–548.

[21] The residential and commercial subsectors include dimensions for Census Division and building types, because energy consumption and efficiency characteristics vary across these dimensions. For the transportation, industrial, and generation sectors, regional differences are judged to be less important. The total number of subsectors used in index construction is 2,539. For the residential sector, the number of subsectors is 731 (9 Census Divisions times 3 building types times 27 specific end uses plus 2 aggregated end uses—marketed renewable energy and other fuels. For the commercial sector the number of subsectors is 1,785 (9 divisions times 11 building types times 18 end uses plus 3 aggregated end uses—other fuels, biomass, and renewable energy. For the transportation sector there are 10 subsectors, for the industrial sector there are 13 subsectors, and for the electricity generation sector there are no subsectors.

$$ACEI^i_t = ACEI^i_{t-1} \exp\left[\sum_{j=1}^{n(i)} 0.5\left(\frac{e^i_{j,t}}{\sum_j e^i_{j,t}} + \frac{e^i_{j,t-1}}{\sum_j e^i_{j,t-1}}\right)\ln\left(\frac{I^i_{j,t}}{I^i_{j,t-1}}\right)\right] \quad (2)$$

Thus, $\Sigma_j e^i_{j,t}$ represents total energy consumption for sector i in year t, calculated by summing across its component subsectors. Both the economy-wide aggregate and the sector indexes are calculated.[22]

[22] A different method for developing the economy-wide index would be to use a two-stage procedure of first computing sectoral indexes and then aggregating the indexes to form the economy-wide measure. In general, the two-stage Törnqvist aggregation of sector indexes to the economy-wide level will differ from the single-stage aggregation across all sectors and subsectors. In practice, for the *AEO2002* projections described here, the difference is insignificant, differing only in the 6th significant digit.