Can Efficiency Improvements Reduce Resource Consumption?

A Historical Analysis of Ten Activities

Jeffrey B. Dahmus[1,2 *] and Timothy G. Gutowski[3]
[1] Materials Systems Laboratory, [2] MIT Energy Initiative,
[3] Department of Mechanical Engineering
Massachusetts Institute of Technology
77 Massachusetts Avenue, Room E40-417
Cambridge, MA 02139
jdahmus@mit.edu and gutowski@mit.edu

Abstract

This work explores the historical effectiveness of efficiency improvements in reducing humankind's consumption of energy resources. Ten activities are analyzed, including pig iron production, aluminum production, nitrogen fertilizer production, electricity generation from coal, oil, and natural gas, freight rail travel, passenger air travel, motor vehicle travel, and residential refrigeration. The data and analyses presented here demonstrate the dynamic interplay between technological innovation, market forces, and government policy. They also show that historically, over long time periods, improvements in efficiency have not succeeded in outpacing increases in the quantity of goods and services provided. Thus, the end result over these time periods has been, not surprisingly, a sizeable increase in the consumption of energy resources across all ten activities. However, there do exist a few examples of shorter, decade-long time periods in which improvements in efficiency were able to match or outpace increases in quantity. In these cases, efficiency mandates, price pressures, and industry upheaval led to periods of reduced resource consumption. These cases suggest that with appropriate incentives, including, for example, efficiency mandates and price mechanisms, future resource consumption, and its associated environmental impacts, could be stabilized and even reduced.

Keywords: efficiency, resource consumption, *IPAT* identity, eco-efficiency, rebound effect

* Corresponding Author, phone (408) 221-8598

Introduction

Efficiency improvements are often touted as effective and unobtrusive means of reducing resource consumption. For many, and perhaps in particular for engineers, the idea that reductions in resource consumption, and thus a reduction in the associated environmental impacts of resource consumption, can be achieved through technology-based solutions is especially attractive. As such, improving efficiency is often mentioned as a critical component of green engineering or design for environment (DfE) guidelines for engineers. Graedel and Allenby in fact cite modifying the amount of environmental impact per unit of output – a measure of environmental efficiency – as a central tenet of industrial ecology, as well as offering "the greatest hope for transition to sustainable development" (Graedel and Allenby, 1998). Others, including Anastas and Zimmerman, include energy and resource efficiency as a green engineering principle (Fiksel 1996, Otto and Wood 2001, Anastas and Zimmerman 2003). More broadly, such efficiency improvements have been embraced as "win-wins" in that they allow for both economic and environmental progress to occur (DeSimone and Popoff 1997, OECD 1998, WBCSD 2000).

While encouraging engineers to focus on efficiency improvements certainly has economic and social benefits, the notion that such improvements lead to reductions in resource consumption is less certain. After all, engineers have successfully realized efficiency improvements for centuries; yet, these product- and process-level efficiency improvements have generally not resulted in absolute system-level reductions in resource consumption. Instead, perhaps not surprisingly, resource consumption has continued to increase, driven by growing population and increasing affluence, among other factors. Clearly, in order for efficiency improvements to reduce resource consumption, these technological innovations must outpace increases in the quantity of goods and services provided. However, this requirement is made more difficult by the fact that efficiency and quantity are not entirely independent, and can in fact drive one another. Perhaps the best-known example of this interdependence is the rebound effect, as described by economist W. Stanley Jevons in the 1800s, in which improved efficiency actually leads to increased consumption of a resource (Jevons 1865). The existence of such relationships could mean that the product- and process-level efficiency improvements focused on by engineers, and recommended by green engineering guidelines, may in fact play a role in increasing, not decreasing, resource consumption at the system level. This tension between the engineer's view of efficiency improvements – in which efficiency improvements are seen as reducing resource consumption – and the economist's view of efficiency improvements – in which efficiency improvements are seen as potentially increasing resource consumption – is a topic of much debate (Herring 1998, Smil 2003, Herring 2006).

The work presented here addresses this tension, investigating the historical relationship between the product- and process-level efficiency improvements made by engineers and the absolute system-level impacts on resource consumption. Historical data on efficiency and on the quantity of goods and services provided for ten different engineering activities are analyzed. Periods in which efficiency improvements did outpace increases in quantity, thus resulting in periods of reduced consumption of energy resources, are identified. These particular periods are then analyzed to gain insights into how future efficiency improvements can be leveraged to realize reductions in resource consumption.

Background

In framing the relationship between efficiency improvements and resource consumption, the *IPAT* identity can be used. This identity disaggregates impact (I) into the product of population (P), affluence (A), and technology (T). It can be written as

$$Impact = Population \ x \ \frac{GDP}{Population} \ x \ \frac{Impact}{GDP} \quad , \tag{1}$$

where affluence is represented as the Gross Domestic Product (GDP) per person and technology is represented as the environmental impact per unit of GDP (Graedel and Allenby 2003). While this disaggregation allows one to focus on the individual factors that contribute to humankind's impact on the earth, it is important to note that these terms are not independent (Ehrlich and Holdren 1972).

Many variants on the *IPAT* identity exist, variants that often either combine terms for added simplicity, or further disaggregate terms for added resolution. In discussing the role of efficiency improvements in reducing resource consumption, the basic *IPAT* identity shown in (1) can be further disaggregated to,

$$Impact = Population \ x \ \frac{GDP}{Population} \ x \ \frac{Quantity}{GDP} \ x \ \frac{Resources}{Quantity} \ x \ \frac{Impact}{Resources} \quad , \tag{2}$$

where "Quantity" refers to the quantity of goods and services provided in a society and "Resources" refers to the amount of resources consumed. It can be easily shown that other variants of the *IPAT* identity, including the Kaya Identity and the ImPACT Identity, are in fact contained within (2) (Yamaji et al. 1991, Waggoner and Ausubel 2002).

In focusing on the role of technology-based solutions in reducing resource consumption, the first few terms in (2) can be combined, yielding

$$Impact = Quantity \; x \; \frac{Resources}{Quantity} \; x \; \frac{Impact}{Resources} \quad . \tag{3}$$

In focusing on resource consumption, as compared to environmental impact, (3) can be further simplified to

$$Resources = Quantity \; x \; \frac{Resources}{Quantity} \quad . \tag{4}$$

As defined above, the left side of (4) represents the amount of resources consumed, while the first term on the right-hand side represents the quantity of goods and services provided. The second term on the right-hand side of (4), representing the amount of resources consumed per quantity of goods and services provided, is a measure of resource intensity, the inverse of which is resource productivity (Dahlström and Ekins 2005, Huppes and Ishikawa 2005). Resource productivity, also known as resource-use efficiency, represents the quantity of goods and services provided per amount of resources consumed. This is in fact an eco-efficiency, a ratio of economic value to environmental load (Ehrenfeld 2005). Thus, (4) can be rewritten as

$$Resources = Quantity \; x \; \frac{1}{Eco - efficiency} \quad . \tag{5}$$

From (5) it is clear that in order for efficiency improvements to successfully reduce resource consumption, the rate of improvement in eco-efficiency must outpace the rate of increase in quantity. At the same time, in order to maintain economic growth, the quantity of goods and services provided must generally be growing. Thus, in order for efficiency improvements to lead to reductions in resource consumption, the inequality

$$\frac{\Delta e}{e} > \frac{\Delta Q}{Q} > 0 \quad , \tag{6}$$

where e represents efficiency and Q represents quantity, must be satisfied.[1]

Previous Work

Historical trends in efficiency, quantity, and resource consumption have been tracked and analyzed previously. Smil has published a wealth of information on efficiency, including tracking historical efficiency trends across a range of different technologies and activities, from steam engines to pig iron smelting (Smil 1994, Smil 1999, Smil 2001, Smil 2003). Some of Smil's historical efficiency data is in fact used in the analyses presented here. Works by Ayres et al. have also provided in-depth analyses of efficiency improvements over time, looking at the efficiency of technologies and activities including ammonia synthesis, internal combustion engines, and plastic production (Ayres et al. 2003, Ayres and Warr 2005, Ayres et al. 2005).

At the same time, the quantity of goods and services provided has also been tracked, often by industry groups and government agencies. US government agencies ranging from the US Geological Survey to the US Department of Transportation track various quantities, from the amount of certain materials produced to the amount of vehicle-miles travelled, respectively. Smil and Ayres have also tracked the generally increasing quantities of goods and services provided, from the number of motor vehicles in the world to the amount of horsepower used on farms in the US (Smil 1999, Ayres et al. 2003). Clearly, both efficiency and quantity are often tracked, as they can be seen as measures of technological advancement and societal growth.

While historical data on efficiency and quantity has been collected, it is the direct quantitative comparison of these data sets that is of particular interest in this work. As the product of these two values is resource consumption – as shown in (5) – comparing the rate of improvement in efficiency with the rate of increase in quantity, is critical to understanding overall trends in resource consumption. Clearly, the large-scale trends in the consumption of energy resources are well-known, and the fact that overall increases in quantity are outpacing overall improvements in efficiency is not new. However, through a quantitative comparison of these rates of change, across a wide range of different activities and time-periods, the dynamic interplay between technological innovation, market forces, and government policy can be explored. Such analyses allow the rate of improvement in efficiency and the rate of increase in quantity to be compared, both within a single activity and between multiple activities. These analyses also allow periods in which improvements in efficiency did outpace increases in quantity to be identified and analyzed as possible scenarios to be emulated.

The overall approach taken here, which isolates and analyzes the critical factors driving a particular output – namely efficiency and quantity driving resource consumption – bears similarities to decomposition analysis. Works by Waggoner, Wernick, and Ausubel, utilize similar decomposition approaches to disaggregate the critical factors contributing to various metrics, including environmental impact and consumption (Waggoner et al. 1996, Wernick et al. 1997). Decomposition approaches have also been used to identify the critical determinants of changes in quantity – including consumer preference, the material composition of products, and GDP – and to evaluate the importance of each (Roberts 1988). Other decomposition analyses have helped to address the material intensity of use and its relation to economic output (Considine 1991, Cleveland and Ruth 1998). In general, decomposition provides a link between broader aggregate economic or environmental effects and a collection of specific factors that contribute to those effects. These techniques are part of a larger field of decomposition analysis that includes index decomposition analysis – which relies on sector-level or country-level data – and structural decomposition analysis – which relies on input-output tables (Rose and Casler 1996, Ang and Zhang 2000, Hoekstra and van den Bergh 2002). In both approaches, the overall goal, to comprehend the link between a particular metric and the multiple factors that contribute to this metric, remain the same. In the approach used here, resource consumption is decomposed into quantity and efficiency, as shown in (5), and the relative contributions that each of these two factors makes to resource consumption, are analyzed.

Historical Trends in Efficiency and Quantity

Historical efficiency and quantity data were compiled to examine if past improvements in efficiency have been able to outpace past increases in the quantity of goods and services provided. If this had indeed been the case, (6) would have been satisfied, and reductions in resource consumption would have occurred. The data presented here covers ten activities, including pig iron production, aluminum production, nitrogen fertilizer production, electricity generation from coal, oil, and natural gas, freight rail travel, passenger air travel, motor vehicle travel, and residential refrigeration. For each of the activities analyzed, quantity is measured as the quantity of goods or services provided, while efficiency is measured as the quantity of goods or services provided per amount of resource consumed. In each case, the resource consumed is an energy-related resource, from kilograms of coal to GJ of electricity.

The ten activities analyzed here represent a broad cross-section of human activity, and are directly related to a large portion of global economic activity. These activities were selected in part for these very reasons, along with the fact that long time-series data for these activities were available. While data availability did bias the selection of activities towards those that have been in existence for a long time, as well as those for which industry-wide quantity and efficiency data were recorded, the consistency of the findings across these ten distinct activities – as will be seen in Figures 1 through 11 – suggest that the patterns seen in these ten activities are robust and may be applicable to other similar activities.

For each of the ten activities analyzed, the geographic and temporal boundaries of the analyses were quite varied, as summarized in Table 1. Geographic boundaries were drawn to either include the entire world or to include only the US. For goods and services for which an integrated global market exists, as is the case with pig iron, aluminum, and nitrogen fertilizer, global data was used. Using global data for these activities prevents geographic shits in production from impacting the analyses. For goods and services for which an integrated global market does not exist, as is the case with electricity, vehicle travel, and refrigeration, US data was used. For these activities – which tend to be services – changes in the quantity provided generally represent changes in demand, as opposed to any geographic shifts in production.

Temporal boundaries were determined based on both the lifecycle of a technology as well as on data availability. While many of the activities analyzed have undergone radical technological transformations – refrigeration for example has transitioned from ice houses to electric refrigerators – only the most recent technology – in this example, electric refrigerators – is examined. Such limits help to ensure that the goods or services for a given activity remain roughly comparable over the time periods analyzed. However, even with these limits in place, there can still be changes across a range of performance measures, including efficiency, convenience, and safety, among others. While these changes in quality could be captured using multi-attribute utility analysis or hedonic regression modeling, such analyses involve significantly more information, including objective data about performance characteristics as well as subjective data about the value of these performance characteristics. Such analyses are outside the scope of this work. Thus, for simplicity, temporal boundaries are selected to ensure a generally comparable set of goods and services.

Setting temporal boundaries around a single technology also restricts the types of efficiency improvements considered. In particular, while incremental or evolutionary improvements in a given technology are included, substitutions of new technologies are not included. Excluding such changes can lead to lower calculated rates of efficiency improvement. However, such a simplification does avoid the significant informational requirements – as described above – needed to capture changes in the quality of a good or service. Also, the evolutionary efficiency improvements that are captured in this analysis do represent the more common type of efficiency improvement.

In addition to differences in geographic and temporal boundaries, the technological boundaries of the analyses, as well as the boundaries of the activity itself, also differ. Technological boundaries refer to the issue of technology scope, and determine what technological innovations are included in the analysis. For some activities, such as aluminum production, the technological boundary is drawn at the process-level, meaning that only the technological improvements affecting a single process are included. For other activities, such as passenger air travel, the boundary is drawn at the industry-level, meaning that a broad range of innovations, from process improvements to operational changes, are included. These boundaries on technology scope are again often driven by data availability. The boundaries of the activity are typically drawn to include a single industry, for example pig iron or nitrogen fertilizer, or a single market, for example *passenger* air travel or *residential* refrigeration. Limiting the scope to include single industries or markets allows for more straightforward data collection, although it does ignore potential shifts in quantity between different industries or markets. Despite the many different geographic, temporal, technological, and activity-based boundaries used in the analyses presented here, the overall patterns in efficiency, quantity, and resource consumption are pervasive.

Figure 1 plots worldwide pig iron production, measured as the mass of pig iron produced, and efficiency, measured as the mass of pig iron produced per unit of coke consumed in smelting.[2] Figure 2 plots worldwide aluminum production, measured as the mass of aluminum produced, and efficiency, measured as the mass of aluminum produced per unit of electricity consumed in the smelting process.[3] Figure 3 plots worldwide nitrogen fertilizer production, measured as the mass of nitrogen produced, and efficiency, measured as the mass of nitrogen produced per unit of energy consumed in the Haber-Bosch process.[4] The data plotted in Figures 1 through 3 show almost continuous increases in both efficiency and quantity.

Figures 4, 5, and 6 show efficiency and quantity data for electricity generation from coal, oil, and natural gas in the US. These figures plot US production of electricity from a specific fossil fuel, measured in units of electricity produced, and efficiency, measured in units of electricity produced per mass or volume of fossil fuel consumed. In each of these three figures, despite significant disturbances in both efficiency and quantity, the overall trends generally show both efficiency and quantity increasing over time.[5, 6, 7]

Figure 7 plots the efficiency and quantity of freight rail travel by US Class I railroads.[8] Quantity is measured in revenue tonne-kilometers of freight rail travel, while efficiency is measured in revenue tonne-kilometers of freight rail travel produced per volume of fuel consumed.[9] Figure 8 plots the efficiency and quantity of passenger air travel by US airlines. Quantity is measured in available seat-kilometers of passenger air travel, while efficiency is measured in available seat-kilometers of passenger air travel produced per volume of fuel consumed.[10] As in Figures 1 through 6, Figures 7 and 8 again show efficiency and quantity increasing in parallel.

Figure 9 plots efficiency and quantity data for motor vehicle travel in the US.[11] Quantity is measured in vehicle-kilometers of motor vehicle travel, while efficiency is measured in vehicle-kilometers of motor vehicle travel produced per volume of fuel consumed.[12] Figure 10 plots efficiency and quantity data for residential refrigeration in the US.[13] Quantity is measured in hours of refrigeration, while efficiency is measured in hours of refrigeration produced per unit of electricity consumed. Figures 9 and 10 both show an earlier period of declining efficiency, followed by a more recent period of improving efficiency. In both activites, throughout these changes in efficiency, quantity has continued to increase.

FIGURE 1: Pig Iron Production (*Q*) and the Efficiency of Pig Iron Smelting (*e*) (World) [a]

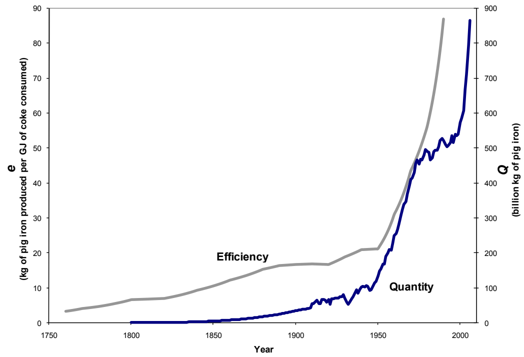


FIGURE 2: Primary Aluminum Production (*Q*) and the Efficiency of Aluminum Smelting (e) (World) [b]

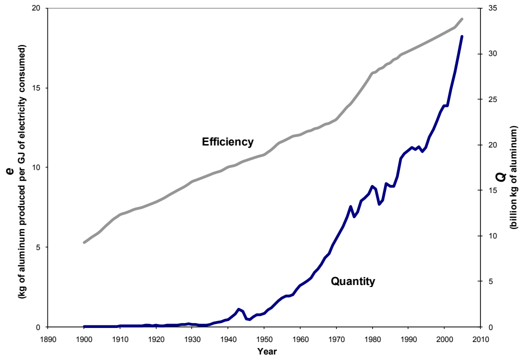


FIGURE 3: Nitrogen Fertilizer Production (*Q*) and the Efficiency of the Haber-Bosch Process (e) (World) [c]

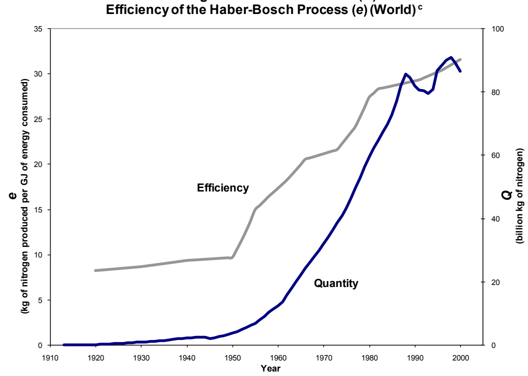


FIGURE 4: Electricity Generation from Coal (*Q*) and the Efficiency of Electricity Generation from Coal (e) (US) [d]

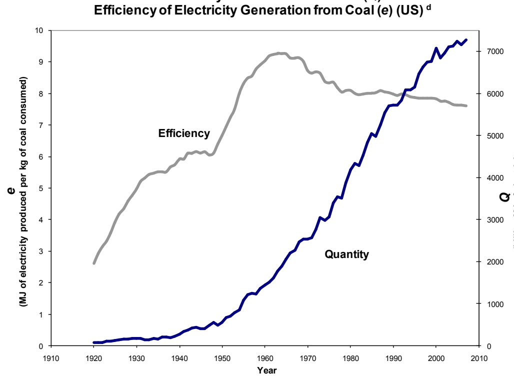


FIGURE 5: Electricity Generation from Oil (*Q*) and the Efficiency of Electricity Generation from Oil (e) (US) [d]

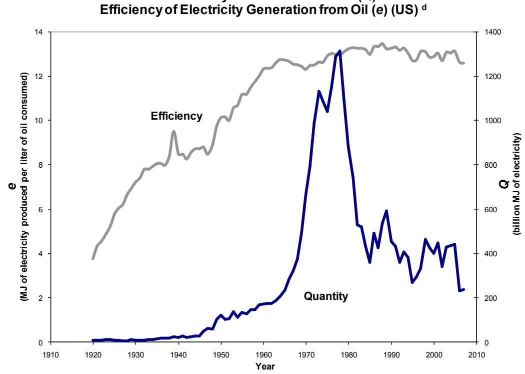


FIGURE 6: Electricity Generation from Natural Gas (*Q*) and the Efficiency of Electricity Generation from Natural Gas (e) (US) [d]

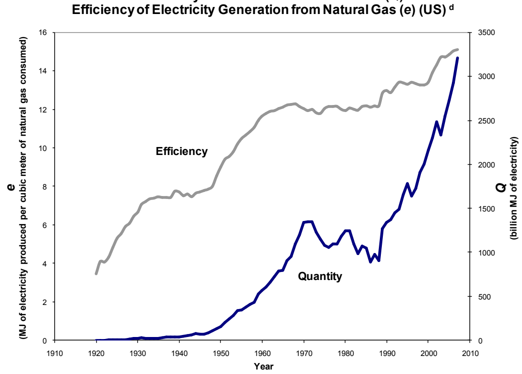


FIGURE 7: Freight Rail Travel (*Q*) and the Efficiency of Freight Rail Travel (e) (US Class I Railroads) [e]

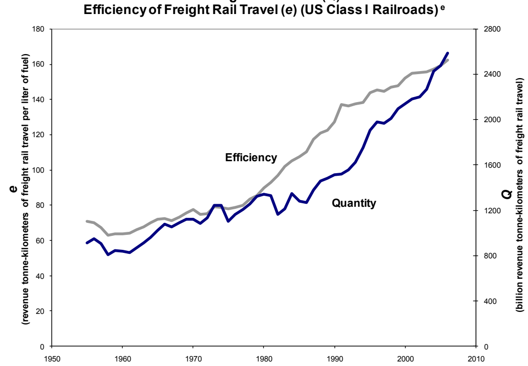


FIGURE 8: Passenger Air Travel (*Q*) and the Efficiency of Passenger Air Travel (e) (US airlines) [f]

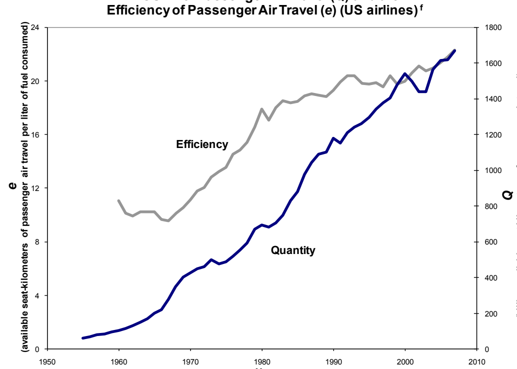


FIGURE 9: Motor Vehicle Travel (Q) and the Efficiency of Motor Vehicle Travel (e) (US) [g]

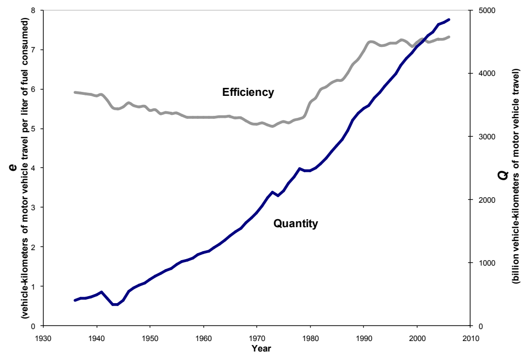


FIGURE 10: Refrigeration (Q) and the Efficiency of Refrigeration (e) (US) [h]

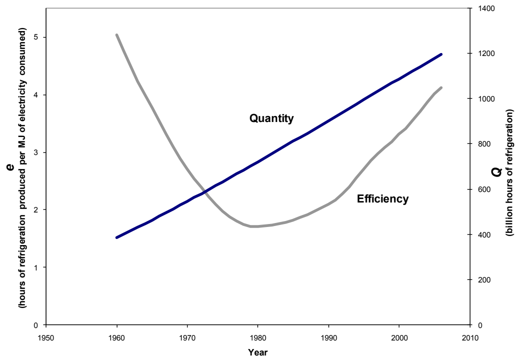


Table 1 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in quantity, $\Delta Q/Q$, for the ten activities analyzed in Figures 1 through 10. Positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in quantity indicate increases in the quantity of goods and services provided. The historical data clearly show that in each of these industries, the average annual $\Delta Q/Q$ exceeded the average annual $\Delta e/e$, meaning that, on average, (6) was not satisfied. Thus, despite significant improvements in efficiency, the resources consumed by each of these activities, as calculated using (5), has increased. Figures in Appendix A clearly show this overall increase in resource consumption over the time periods analyzed here.

Activity	Time Period	Geographic Region	Average Annual $\Delta e/e$	Average Annual $\Delta Q/Q$	Average $\Delta Q/Q$ / Average $\Delta e/e$
Pig Iron	1800-1990	World	1.4%	4.1%	3.0
Aluminum	1900-2005	World	1.2%	9.8%	7.9
Nitrogen Fertilizer	1920-2000	World	1.0%	8.8%	8.9
Electricity					
from Coal	1920-2007	US	1.3%	5.7%	4.5
from Oil	1920-2007	US	1.5%	6.2%	4.2
from Natural Gas	1920-2007	US	1.8%	9.6%	5.5
Freight Rail Travel	1960-2006	US	2.0%	2.5%	1.2
Passenger Air Travel	1960-2007	US	1.3%	6.3%	4.9
Motor Vehicle Travel	1940-2006	US	0.3%	3.8%	11.0
Refrigeration	1960-2006	US	-0.4%	2.5%	---

Table 1: Average annual $\Delta e/e$, average annual $\Delta Q/Q$, and the ratio of the two for ten activities. In these activities, increases in quantity outpace improvements in efficiency by factors ranging from 1.2 to 11.0.

The values in Table 1 can also be shown graphically by plotting the average annual change in quantity versus the average annual change in efficiency, as shown in Figure 11. The solid diagonal line in Figure 11 is the line of constant resource consumption, representing the condition in which the average annual $\Delta e/e$ is equal to the average annual $\Delta Q/Q$. Points above this line represent periods of increasing resource consumption, where (6) is not satisfied, while points below this line represent periods of decreasing resource consumption, where (6) is satisfied. From Figure 11, it is clear that in each of the ten cases examined above, (6) is not satisfied.

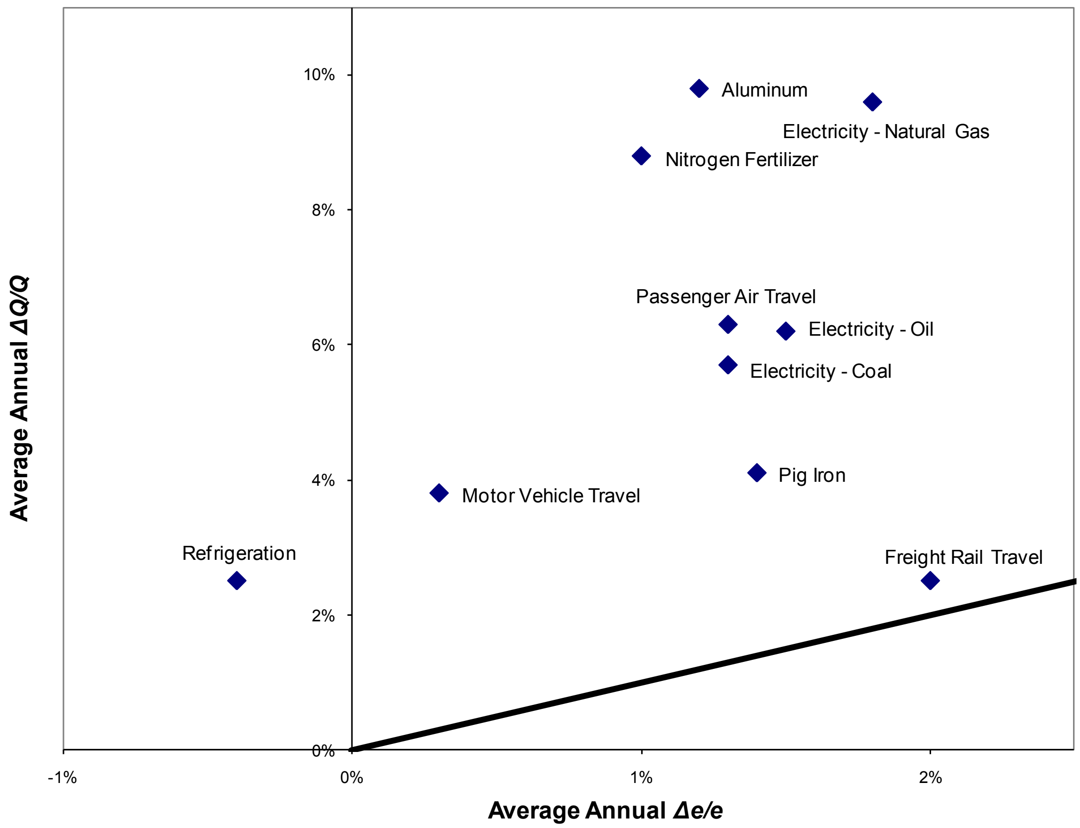


Figure 11: Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for ten activities. The solid diagonal line is the line of constant resource consumption, representing the condition in which the average annual $\Delta e/e$ is equal to the average annual $\Delta Q/Q$.

Decade-by-Decade Analysis

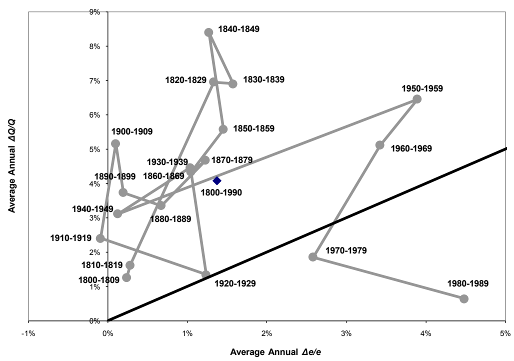
While the long time periods presented above may appear to show little potential for future efficiency improvements to reduce resource consumption, a decade-by-decade analysis of these activities reveals a few time periods in which improvements in efficiency did outpace increases in the quantity of goods and services provided, resulting in periods of decreasing resource consumption. One such example occurs in the case of pig iron. Table 2 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in quantity, $\Delta Q/Q$, for worldwide pig iron production, both overall and on a decade-by-decade basis. As before, positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in quantity indicate increases in the quantity of goods provided.

Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta Q/Q$	Average $\Delta Q/Q$ / Average $\Delta e/e$
Pig Iron	1800-1990	1.4%	4.1%	3.0
	1800-1809	0.2%	1.3%	5.4
	1810-1819	0.3%	1.6%	5.8
	1820-1829	1.3%	7.0%	5.2
	1830-1839	1.6%	6.9%	4.4
	1840-1849	1.3%	8.4%	6.6
	1850-1859	1.5%	5.6%	3.8
	1860-1869	1.0%	4.3%	4.2
	1870-1879	1.2%	4.7%	3.8
	1880-1889	0.7%	3.4%	5.0
	1890-1899	0.2%	3.7%	19.6
	1900-1909	0.1%	5.2%	53.5
	1910-1919	-0.1%	2.4%	---
	1920-1929	1.2%	1.3%	1.1
	1930-1939	1.0%	4.5%	4.3
	1940-1949	0.1%	3.1%	25.7
	1950-1959	3.9%	6.5%	1.7
	1960-1969	3.4%	5.1%	1.5
	1970-1979	2.6%	1.9%	0.7
	1980-1989	4.5%	0.6%	0.1

Table 2: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for worldwide pig iron production over 19 decades. The two decades during which average annual $\Delta e/e$ outpaced average annual $\Delta Q/Q$ are highlighted.

Figure 12 plots the decade-by-decade worldwide pig iron data from Table 2. As in Figure 11, the dark diagonal line in Figure 12 represents a line of constant resource consumption; points above this line represent periods of increasing resource consumption while points below this line represent periods of decreasing resource consumption.

FIGURE 12: Average Annual $\Delta Q/Q$ versus Average Annual $\Delta e/e$ for Pig Iron [a]



As can be seen in Table 2 and in Figure 12, worldwide pig iron production did experience a period of time, from 1970 to 1989, during which improvements in the efficiency of pig iron smelting outpaced increases in the quantity of pig iron produced. During this period, the average annual increase in quantity was a mere 1.2%, far below the historical average of 4.1%. In the latter part of this period, the average annual increase in quantity was at an all-time low of 0.6%. At the same time, the efficiency of pig iron smelting was improving rapidly, at an average annual increase of 3.5%, well above the historical average of 1.4%. It is clear that the dynamics of this time period were certainly unprecedented in the long history of pig iron production. While more recent efficiency data is not available, the fact that by the early 2000s, the average annual increase in quantity had rebounded to over 7%, suggests that this period of reduced resource consumption has not continued to today.

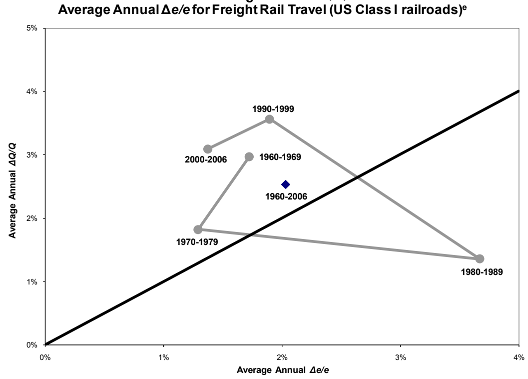
This period from 1970 to 1989 proved to be a turbulent time for the iron and steel industry, marked by slowing worldwide economic growth and the beginning of a geographic shift in production, away from industrialized nations and towards developing countries (Roberts 1988, Hudson and Sadler 1989, Warren 2001, Fenton 2005). A variety of factors, including rising pig iron prices, the greater availability of substitute materials such as plastics and aluminum, and a slowdown in infrastructure building in developed countries, accounted for the slower average annual increases in pig iron quantity during this period (Hudson and Sadler 1989, Mangum et al. 1996, Warren 2001, Tilton 2002).[14] This period was also marked by rising energy and raw material costs, which pressured pig iron producers to become more efficient. Improvements such as the use of pelletized ore, increases in hot blast temperatures, and increases in blast furnace size, all contributed to rapidly improving efficiencies (Ruth 1995, de Beer et al. 1998, Smil 1999, Fenton 2005).

Another activity in which, on a decade-by-decade basis, improvements in efficiency outpaced increases in quantity is freight rail travel. The data for freight rail travel by US Class I railroads, over five time periods from 1960 to 2006, is shown in Table 3, and plotted in Figure 13. The dark diagonal line in Figure 13 represents a line of constant resource consumption.

Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta Q/Q$	Average $\Delta Q/Q$ / Average $\Delta e/e$
Freight Rail Travel	1960-2006	2.0%	2.5%	1.2
	1960-1969	1.7%	3.0%	1.7
	1970-1979	1.3%	1.8%	1.4
	1980-1989	3.7%	1.4%	0.4
	1990-1999	1.9%	3.6%	1.9
	2000-2006	1.4%	3.1%	2.3

Table 3: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for US freight rail travel on a decade-by-decade basis. The time period in which average annual $\Delta e/e$ outpaced average annual $\Delta Q/Q$ is highlighted.

FIGURE 13: Average Annual $\Delta Q/Q$ versus Average Annual $\Delta e/e$ for Freight Rail Travel (US Class I railroads)[e]



As can be seen in Table 3 and in Figure 13, US freight rail travel did experience a period in the 1980s in which improvements in the fuel efficiency of freight rail travel outpaced increases in the quantity of freight rail travel provided. This period, much like the comparable period in pig iron, featured historically-high rates of efficiency improvements, and historically-low rates of quantity growth. Figure 13 clearly shows that the 1980s were an outlier, particularly in terms of the average annual efficiency improvements.

In general, the 1980s marked a renaissance in US freight rail travel, as the financial health of the industry improved considerably during this period (Pauly et al. 1980, Duke et al. 1992, Braeutigam 1993). This industry revitalization was driven by various factors, the most important of which was government legislation that deregulated the rail industry. In particular, the Staggers Rail Act of 1980, which, among other things, gave rail companies the freedom to set their own rates and to shut down unprofitable rail lines, helped the rail industry to both increase revenue and reduce costs (Duke et al. 1992, Braeutigam 1993). These actions also had important impacts on fuel efficiency, as fewer lines, now carrying more freight, proved to be more efficient (Business Week 1984, Flint 1986).[15] In addition to industry deregulation, technological improvements also contributed to efficiency gains. For example, the increased use of computers for optimized train scheduling and routing, and the introduction of new rail car designs that increased both the type and amount of freight that could be transported by a single train, both played a role in improving efficiency during the 1980s (Shedd 1984, Omaha World-Herald 1984, Williams 1985, Houston Chronicle 1986, Flint 1986, Duke et al. 1992).[16]

While the other transportation activities included in Table 1 and Figure 11, namely US passenger air travel and US motor vehicle travel, never experienced a decade in which average annual improvements in efficiency outpaced average annual increases in quantity, the dynamics of these two activities over time is interesting to examine in greater depth. Table 4 shows a decade-by-decade breakdown of average annual changes in efficiency and average annual changes in quantity for passenger air travel. Figure 14 plots this data, with the dark diagonal line again representing a line of constant resource consumption.

Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta Q/Q$	Average $\Delta Q/Q$ / Average $\Delta e/e$
Passenger Air Travel	1960-2007	1.3%	6.3%	4.9
	1960-1969	-1.6%	15.6%	---
	1970-1979	4.7%	5.3%	1.1
	1980-1989	1.4%	5.2%	3.8
	1990-1999	0.5%	3.0%	5.8
	2000-2007	1.5%	1.6%	1.0

Table 4: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for US passenger air travel on a decade-by-decade basis. In this activity, there are no decades in which average annual $\Delta e/e$ outpaced average annual $\Delta Q/Q$.

FIGURE 14: Average Annual $\Delta Q/Q$ versus Average Annual $\Delta e/e$ for Passenger Air Travel (US airlines) [f]

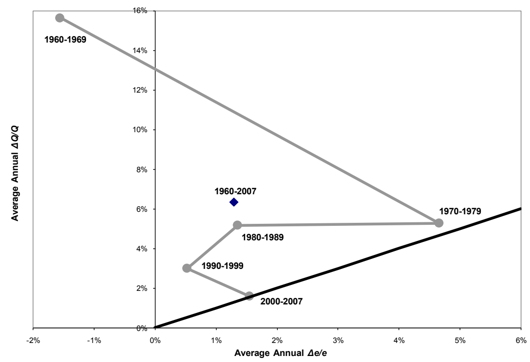
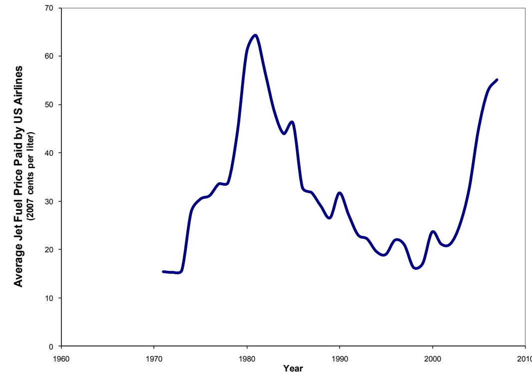


FIGURE 15: Historical Jet Fuel Prices [f]



While US passenger air travel has never reached the state where average annual changes in efficiency exceeded average annual changes in production , there were two periods – the 1970s and the 2000s – that came relatively close to satisfying (6). The more recent of these, the period from 2000 to 2007, was marked by increased rates of efficiency improvement and a historically-low rate of quantity increases. The low average annual growth in quantity was due to a two to three year decline in passenger air travel, as seen in Figure 8, which was driven by numerous factors, including the economic slowdown of the early 2000s, the events of September 11th, 2001, the start of military action in Iraq, and the outbreak of severe acute respiratory syndrome (SARS) in Asia. This decrease in average annual quantity growth followed a four-decade-long trend of declining growth rates, as seen in Table 4. Whether or not this slower growth rate will continue remains to be seen. However, given the global recession, rising operating costs for airlines, rising air travel costs for consumers, and ongoing financial instability in the industry as a whole, it appears probable that average annual quantity growth will remain low (Economist 2008). On the efficiency side, the increase in the rate of efficiency improvements in the 2000s was driven in large part by rising jet fuel prices, as seen in Figure 15. With fuel costs representing over a quarter of operating costs, increases in jet fuel prices led to both operational changes, such as reducing cruising speeds and improving air traffic management, and technological changes, such as developing more fuel-efficient airframes and engines (IPCC 1999, ATA 2007, Heimlich 2007, Economist 2008, Wilen 2008).[17]

The other period in which US passenger air travel nearly satisfied (6) was from 1970 to 1979. As compared to the 1960s, the 1970s were marked by a significantly slower rate of quantity growth and a significantly higher rate of efficiency improvement. This increase in the rate of efficiency improvement was again driven in large part by increasing jet fuel prices, as seen in Figure 15 (Morrison 1984). Although there are other influences on fuel efficiency besides fuel prices, in the case of passenger air travel, the link between the two is quite strong; as seen in Figures 14 and 15, average annual efficiency improvements increased during periods of increasing real jet fuel prices and decreased during periods of decreasing real jet fuel prices.

Table 5 shows a decade-by-decade breakdown of average annual changes in efficiency and average annual changes in quantity for US motor vehicle travel. Figure 16 plots this decade-by-decade data. Like passenger air travel, motor vehicle travel has made strong movements towards the line of constant resource consumption, yet has never realized a period in which (6) was satisfied.

Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta Q/Q$	Average $\Delta Q/Q$ / Average $\Delta e/e$
Motor Vehicle Travel	1940-2006	0.3%	3.8%	11.0
	1940-1949	-0.5%	5.3%	---
	1950-1959	-0.5%	5.2%	---
	1960-1969	-0.3%	4.3%	---
	1970-1979	0.4%	3.8%	9.6
	1980-1989	2.4%	3.2%	1.3
	1990-1999	0.5%	2.5%	5.2
	2000-2006	0.5%	1.6%	3.4

Table 5: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for motor vehicle travel on a decade-by-decade basis. In this activity, there are no decades in which average annual $\Delta e/e$ outpaced average annual $\Delta Q/Q$.

FIGURE 16: Average Annual $\Delta Q/Q$ versus Average Annual $\Delta e/e$ for Motor Vehicle Travel (US data) g

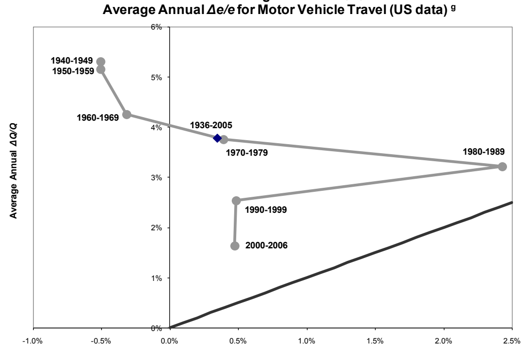
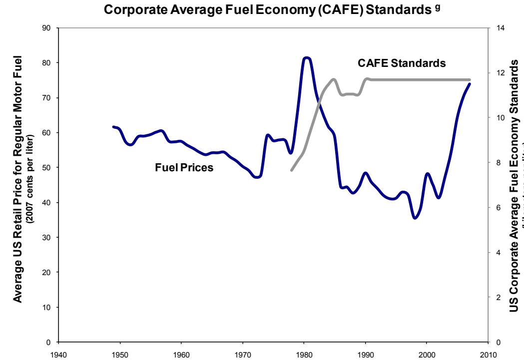


FIGURE 17: Historical Motor Fuel Prices and Corporate Average Fuel Economy (CAFE) Standards g



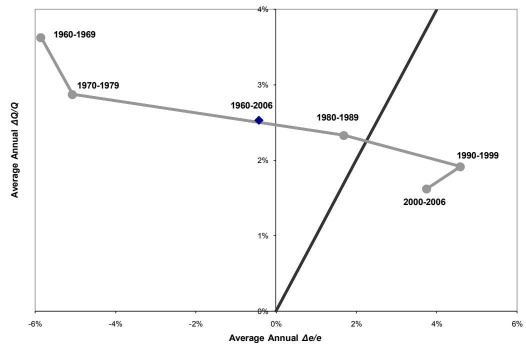
Over the almost seven decades shown in Table 5 and Figure 16, the average annual change in efficiency for US motor vehicle travel has varied considerably. From the 1940s through the 1960s, efficiency declined, as motor vehicles became larger and more powerful.[18] In the 1970s and early 1980s, consumer concerns about gasoline availability, higher gasoline prices, and government legislation in the form of Corporate Average Fuel Economy (CAFE) standards, led to an extended period of improving efficiency.[19] Figure 17 clearly shows both increasing real gasoline prices as well as increasing CAFE requirements during this time period. This trend in efficiency did move motor vehicle travel closer to the line of constant resource consumption, as shown in Figure 16. However, in the 1990s and early 2000s, consumer demand for larger and better-performing vehicles, lower gasoline prices, and the lack of updated CAFE legislation allowed the average annual efficiency improvements to decline considerably in magnitude (Wald 2006). Meanwhile, throughout these periods of changing efficiency, the quantity of US motor vehicle travel has increased considerably, as both the number of motor vehicles and the miles traveled per motor vehicle have increased. However, as in the case of passenger air travel, the rate of increase in the quantity of vehicle-miles travelled has decreased in each decade; if this trend continues, stabilizing or reducing resource consumption in US motor vehicle travel could become easier.

One final case in which improvements in efficiency did outpace increases in quantity on a decade-by-decade basis, is residential refrigeration in the US. Table 6 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in quantity, $\Delta Q/Q$, for US residential refrigeration, both overall and on a decade-by-decade basis. Figure 18 plots this data.

Activity	Time Period	Average Annual $\Delta e/e$	Average Annual $\Delta Q/Q$	Average $\Delta Q/Q$ / Average $\Delta e/e$
Refrigeration	1960-2006	-0.4%	2.5%	---
	1960-1969	-5.9%	3.6%	---
	1970-1979	-5.1%	2.9%	---
	1980-1989	1.7%	2.3%	1.4
	1990-1999	4.6%	1.9%	0.4
	2000-2006	3.7%	2.5%	0.7

Table 6: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for US residential refrigeration on a decade-by-decade basis. The time periods in which average annual $\Delta e/e$ outpaced average annual $\Delta Q/Q$ are highlighted.

FIGURE 18: Average Annual *ΔQ/Q* versus Average Annual *Δe/e* for Refrigeration (US data) [h]



From Figure 18, it is clear that residential refrigeration in the US did succeed in crossing below the line of constant resource consumption. The efficiency trends show that prior to the 1980s, refrigerator efficiency decreased, as refrigerators increased in size and added additional features (Rosenfeld 1999). However, after this period, efficiency improved considerably, driven primarily by a series of state and federal efficiency mandates on appliances.[20] At the same time, the average annual increase in quantity has continued at a steady rate, as both the number of American households and the hours of refrigeration used per household, have increased.[21]

These decade-by-decade analyses show that in some specific activities, decade-long periods did occur in which improvements in efficiency successfully outpaced increases in quantity, meaning that (6) was satisfied and reductions in the consumption of energy resources were realized.

Behind Changes in Efficiency and Quantity

Before examining the circumstances behind these cases in greater detail, the means by which changes in efficiency and quantity come about, will first be explored. While there are many drivers of such changes, including some mentioned previously, such as price pressures and efficiency mandates, this section focuses on the mechanisms by which such changes are realized. Understanding how these changes in efficiency and quantity actually come about, and in what ways these changes are correlated, helps to explain the complexity of actually satisfying (6).

Efficiency

Improvements in efficiency can be realized through a number of different means, including technological innovations, learning effects, and capacity effects, among others. In many cases, these efficiency improvements are in fact tied to changes in quantity.

Technological Innovation

Technological innovation is frequently behind both evolutionary and revolutionary improvements in performance. Often, such performance improvements, when plotted over time, are said to follow an S-shaped technology curve (Ulrich and Eppinger 2000). Such curves typically show limited performance improvement at the start of a new technology, as companies and industries first become aware of an innovation and begin working on it. As the technology becomes more widely disseminated and more resources are applied to the problem, a period of rapid improvement ensues. Finally, there is a plateau in performance, as technologies mature and reach their practical and/or thermodynamic limits (Otto and Wood 2001). In the mature region of the S-curve, further efficiency improvements can sometimes occur by switching to a new technology, which corresponds to jumping to a new S-curve (Foster 1986, Grübler 1998).

As an example, consider the case of worldwide nitrogen fertilizer production. The invention of the Haber-Bosch process for ammonia synthesis, developed and commercialized in the early 1900s, represented a revolution in nitrogen production, and a jump to a new S-curve.[22] While other industrial methods of nitrogen production did already exist, the Haber-Bosch process was significantly more energy efficient (Tamaru 1991). By the mid-1920s, it had become the most common means of producing nitrogen (Smil 2001).

Following its invention, efficiency improvements in the Haber-Bosch process have roughly followed an S-shaped technology curve, as can be seen in Figure 3. These efficiency improvements have been realized through a broad range of technological innovations, including the use of natural gas instead of coal as a feedstock, the design of improved reactors, the recovery of waste heat, the use of centrifugal compressors instead of reciprocating compressors, and the development of improved catalysts, among others (Dybkjaer 1995, Smil 1999, Smil 2001). As the Haber-Bosch process nears its 100th anniversary, efficiency improvements may be reaching a plateau. Such leveling would not be surprising, as the process is nearing its stoichiometric efficiency limit of 39.4 kg of nitrogen produced per GJ of energy consumed (Smil 2001).

Learning Effect

Efficiency improvements can also come about through improvements in the application of existing technologies. This type of efficiency improvement can be attributed to learning and/or experience, and is often referred to as “learning by doing” or “learning by using” (Grübler 1998, Ruttan 2001). Learning occurs when the unit cost of production decreases as cumulative experience, often measured as cumulative output quantity, increases (Argote and Epple 1990). Originally identified in the aircraft industry, learning effects have been seen in many different activities, from shipbuilding to power plant construction (Searle 1945, Joskow and Rose 1985).[23] Through learning, cumulative quantity can drive efficiency; thus, in this case, quantity and efficiency are positively correlated.

Economies of Scale

While learning effects can lead to efficiency improvements based on the cumulative output quantity, economies of scale can lead to efficiency improvements based on the quantity outputted at a given time. Economies of scale occur when the unit cost of production decreases as the quantity produced at a given time increases. Thus, when larger quantities of goods and services can be produced more efficiently than smaller quantities of goods and services, economies of scale are said to exist. With economies of scale, quantity drives efficiency, providing another means by which the terms in (6) can be positively correlated.

In the case of worldwide pig iron production, one of the reasons behind the efficiency improvements of the 1970s and 1980s was the increase in blast furnace size. Blast furnaces have in fact been increasing in size for centuries, having gone from internal volumes around 20 cubic meters in the early 1700s, to internal volumes around 5000 cubic meters by the 1980s (Smil 1999). While the internal volumes of blast furnaces increased by a factor of 250, the energy requirements of blast furnaces increased by a smaller factor, due to both technological innovations and economies of scale (Smil 1999). Such economies of scale helped to improve the efficiency of pig iron production as production quantities increased.

Capacity Effect

While longer-term efficiency improvements are largely driven by technological innovation and learning effects, shorter-term efficiency changes can come about through market dynamics, such as through dips or surges in quantity. In some cases, short-term efforts to scale-back quantity can lead to an improvement in efficiency, as operations are streamlined and less-efficient equipment is shelved. Conversely, short-term efforts to scale-up quantity can lead to a decline in efficiency, as all available equipment, including less-efficient equipment, is brought into use. In general, this negative correlation between quantity and efficiency appears to be brought about by dynamic market shifts, and is most commonly seen in industries with high capital costs and/or long lead-times for capital equipment.

As an example, consider the case of US passenger air travel in the early 2000s. With the precipitous decline in passenger air travel during this time, airlines, facing a surplus of capacity, scaled-back operations by removing excess aircraft from service (Perez et al. 2003, Setaishi 2003, Wong 2003). In general, the planes that were the most costly to operate, which often corresponded to the planes that were the least fuel efficient, were parked, thereby increasing overall fuel efficiency in the short-term.[24] Thus, in this situation, sharp decreases in quantity drove short-term efficiency gains, as airlines adapted to changing market conditions (McCartney and Carey 2003).

While in the case of US passenger air travel, efficiency improved as quantity decreased, the opposite can also occur. Consider the case of freight rail travel in the late 1980s and early 1990s, a period marked by increases in the quantity of revenue tonne-kilometers of freight rail travel provided. This increase in quantity led to an increase in demand for locomotives, which was in turn met both by increasing the production of new, more-efficient locomotives, as well as by increasing the repair and refurbishment of older, less-efficient locomotives, some of which had previously been idled (Holusha 1989, Kruglinski 1993). Thus, this surge in quantity pushed older, less-efficient machines back into use, contributing to a decrease in average annual efficiency gains. Over longer time periods, more new locomotives were brought into use to meet the surging demand. However, in the short term, quantity and efficiency were negatively correlated.

Quantity

Much like changes in efficiency, changes in quantity can also be realized through many different means, including consumers, consumer demand, and economic growth, among others.

<u>Consumers and Consumer Demand</u>

It is clear that consumers have a large impact on the quantity of goods and services provided. As the population of consumers increases, and/or as the affluence of consumers increases, quantity typically increases to meet this surging demand.

Changing consumer taste can also play an important role in quantity. For example, in the case of US passenger air travel, the number of available seat-kilometers produced has been affected by changes in consumer preferences, as consumers have increasingly chosen air travel over other transportation options, including bus, train, and boat travel. Of course, these changing consumer attitudes have themselves been driven by various factors, including technological innovations that have led to improvements in the safety, cost, and convenience of air travel. Had air travel not improved, it is likely that consumer preferences, and quantity increases to keep pace with consumer preferences, would not have changed as dramatically.[25]

Economic Growth

Economic growth also clearly plays a large role in increasing the quantity of goods and services provided. In general, economic growth leads to greater affluence which, in the case of normal goods and services, leads to higher quantities of goods and services. While economic growth drives quantity, efficiency improvements can in fact drive economic growth (Brooks 1990, Saunders 1992, Saunders 2000, Stern 2004, Ayres and Warr 2005). Although many models of economic growth, including the Neo-classical growth model by Solow, do not include energy as a factor of production, other growth models have been developed that do include energy, and in some cases energy efficiency, as factors of production (Solow 1956, Saunders 1992, Saunders 2000, Ayres 2005). While it is fair to say that consensus on this inclusion has not yet been reached, the general idea, that efficiency improvements lead to technological progress which in turn leads to economic growth, appears solid (Brooks 1990, Saunders 1992, Saunders 2000, Ayres and Warr 2005). Thus, through economic growth, efficiency and quantity are again positively correlated.

Rebound Effect

Another mechanism linking efficiency and quantity is the rebound effect. In the 1800s, Jevons observed that improvements in efficiency can in fact lead to increases in the quantity of goods or services provided. Observing coal mining in the United Kingdom, Jevons wrote,

> "It is wholly a confusion of ideas to suppose that the economical use of a fuel is equivalent to a diminished consumption. The very contrary is the truth." (Jevons 1865).

This idea, alternately known as "Jevons' Paradox," the "rebound effect," and the "take back effect," has been the subject of much debate in the economics and energy policy literature (Herring 1998, Hertwich 2005, Herring 2006). At its root however, is the idea that efficiency improvements lead to a decrease in the effective price of a good or service. This price reduction, given a sufficient price elasticity of demand, leads to increased demand, and, in order to meet this demand, an increase in the quantity of goods and services provided.

The mechanisms behind the rebound effect can be examined at both the microeconomic and macroeconomic level. At the microeconomic level, the decrease in the effective price of a good or service resulting from an improvement in efficiency leads to both a substitution effect and an income effect. In the case of the substitution effect, in which the level of utility remains constant, more of the now less-expensive good or service is consumed instead of other goods and services (Pindyck and Rubinfeld 2001, Lovell 2004). In the case of the income effect, in which the level of utility increases, more of all goods and services are consumed, reflecting an increase in real purchasing power (Pindyck and Rubinfeld 2001, Lovell 2004). In both cases, exactly how much more is consumed depends on the price elasticity of demand for these goods and services.[26] At the macroeconomic level, efficiency improvements lead to broader effects, including economy-wide changes in the price of other goods and services and, as discussed previously, economic growth (Brookes 1990, Brookes 2000, Birol and Keppler 2000, Greening et al. 2000).

Discussions about the rebound effect often come down to a debate about the size of the rebound. Some argue that the size of the rebound is insignificant, meaning that efficiency improvements of a given percentage will lead to reductions in resource consumption of approximately the same percentage (Lovins 1988, Grubb 1990, Grubb 1992). Others argue that the size of the rebound is often sufficiently large to be of significance and that in some cases, an improvement in efficiency can in fact lead to an increase in resource consumption (Khazzoom 1980, Khazzoom 1982, Khazzoom 1987, Khazzoom 1989, Brookes 1990, Brookes 1992). While efforts have been made to quantify the rebound effect, these measurements generally only take into account the microeconomic effects, also known as the direct rebound effect, not the macroeconomic or indirect rebound effects.

The size of the direct rebound effect can vary greatly, depending on the price elasticity of demand, which in turn depends on many factors, including the economic actors involved, the goods or services in question, and the length of time since the efficiency improvement. In a survey of measured direct rebound effects in the US, some categories, such as appliances or "white goods", showed essentially no rebound, while other categories, including automobile transport, showed noticeably larger rebound (Greening et al. 2000). In the case of automobile transport, the rebound effect, expressed as the percentage increase in consumption resulting from a 100% improvement in efficiency, was estimated to be between 10 and 30% (Greening et al. 2000). Research into the magnitude of the direct rebound for other goods and services has, in some cases, shown significantly larger rebounds, particularly among lower-income populations, including those in developing countries (Milne and Boardman 2000, Roy 2000). While many of the measurements of direct rebound, including the ones mentioned above, have focused on rebound in the residential and transportation sectors, there have also been some attempts to measure rebound in industry. Estimates of direct rebound in industry resulting from improvements in energy efficiency vary, depending on country, energy prices, and measurement approach, but generally range from 0 to 25% (Berkhout et al. 2000, Greening et al. 2000, Bentzen 2004). Accurate measurements of the size of the complete rebound effect, including direct and indirect effects, are difficult given the many factors involved and the broad range of macroeconomic consequences of efficiency improvements (Greening et al. 2000, Smil 2003).

Discussion

There are clearly many mechanisms by which changes in efficiency and quantity can occur. It is also clear that changes in efficiency and quantity are often correlated, meaning that the terms in (6) are not independent. Thus, in order to reduce resource consumption, one cannot simply focus on a single term in (5), but must instead approach this as a system problem.

In examining the activities presented here, it is important to identify and understand the circumstances under which efficiency improvements were able to outpace increases in quantity. If such conditions can be emulated, there exists the possibility that future efficiency improvements may also lead to reductions in the consumption of energy resources.

In each of the periods of reduced resource consumption presented here, different circumstances drove each case. For worldwide pig iron production and US freight rail travel, the periods of reduced resource consumption corresponded with turbulent times in their respective industries. In the case of worldwide pig iron production, volatile fuel prices and a weak global economy led to this instability, while in the case of US freight rail travel, deregulation led to industry upheaval. For US residential refrigeration, a series of increasingly-stricter efficiency mandates, set forth by the government, led to a prolonged period of reduced resource consumption in the 1990s and early 2000s. Of these different circumstances, it appears that only one of them, namely efficiency mandates, is reproducible, and thus represents a potential approach for future reductions in resource consumption.

If the scope of interest is expanded to include periods in which resource consumption was roughly stabilized, activities such as US passenger air travel and US motor vehicle travel can also be included. For US passenger air travel, periods of relatively stable resource consumption corresponded with periods of increasing jet fuel prices. For US motor vehicle travel, both fuel prices and efficiency mandates contributed to a period of stabilized resource consumption. In light of these cases, price pressures may also prove to represent a repeatable approach for future reductions in resource consumption.

Efficiency Mandates

In attempting to use efficiency mandates to realize reductions in resource consumption, the size of the rebound effect can be critical to success. With little or no rebound, both direct and indirect, efficiency mandates can lead to a case in which (6) is satisfied. However, with more considerable rebound, efficiency mandates may, at best, lead to reductions in resource consumption that are smaller in magnitude than expected; at worst, efficiency mandates may lead to larger overall resource consumption. In fact, efficiency mandates could lead to greater resource consumption more quickly than in the absence of efficiency mandates.

US residential refrigeration appears to be an ideal candidate for reduction in resource consumption through efficiency mandates, as appliances exhibit essentially no direct rebound (Greening et al. 2000). As the efficiency of refrigerators improves, the effective price of refrigeration decreases. In response, depending on the price elasticity of demand, consumers may choose to increase their utilization of refrigerators and/or increase their ownership of refrigerators (Khazzoom 1982). However, since refrigerators typically run constantly, increasing utilization is difficult. Increasing ownership is possible through the use of additional refrigerators; however, while the percentage of US households that use more than one refrigerator is increasing, over three-quarters of US households still find one refrigerator to be sufficient (US DOE 2005). With low price elasticities of demand in both utilization and ownership, there exists little rebound. Thus, efficiency mandates have worked very well in the case of residential refrigeration in the US.[27]

Efficiency mandates for other goods and services with little rebound may also prove effective. For example, efficiency mandates on other appliances, including dishwashers and laundry machines, may lead to reductions in resource consumption. US motor vehicle travel, with a direct rebound effect estimated to be between 10 and 30%, may also represent a case in which efficiency mandates can lead to the reduced consumption of energy resources (Greening et al. 2000). While in this case, the existence of rebound effects may erode some of the overall reduction in resource consumption, efficiency mandates on motor vehicles may still prove to be useful. Indeed, past efficiency mandates on motor vehicles in the US did play some role in helping to move motor vehicle travel closer to the line of constant resource consumption in the 1970s and 1980s, as seen in Figure 16. In general, applying efficiency mandates to activities and situations with limited rebound seems to be a viable approach to satisfying (6), and thus to reducing resource consumption.

Price Pressures

Price pressures also appear to be a promising approach to realizing reductions in resource consumption. In the case of non-durable goods, price increases can lead to limited decreases in demand in the short term, and efficiency improvements in the long term. While these efficiency improvements resulting from price increases can eventually lead to increases in demand through the rebound effect, the initial decrease in demand that price pressures induce may serve to balance out this later increase in demand. In this regard, efficiency improvements that come about through price mechanisms may have an advantage over efficiency improvements that come about through efficiency mandates.

In the case of US passenger air travel, price pressures - in the form of increased jet fuel prices – along with other effects, did help lead to a couple periods of relatively stable resource consumption. During these periods, with no real substitutes for jet fuel, passenger airlines were forced to find other means by which to compensate for rising fuel prices. In the short term, these approaches included passing on higher costs to consumers, through measures such as fuel surcharges, and implementing operational improvements to reduce fuel demand, such as reducing aircraft weight; in the longer term, these approaches included making technological changes to reduce fuel demand, such as investing in more fuel efficient airframes and engines (Pindyck and Rubinfeld 2001, Sharkey 2004, Heimlich 2007, Prada 2008). Thus, in this case, price pressures on jet fuel did help to spur longer-term improvements in efficiency, and a stabilization in resource consumption.

Using price pressures to reduce resource consumption for other goods and services may also prove successful. For example, in the case of US motor vehicle travel, increases in the price of motor fuel could lead to a small drop in demand in the short term, and efficiency improvements in the long term (Pindyck and Rubinfeld 2001, Krueger 2005). Recent market trends have provided an interesting case study, as the real price of motor fuel in the US has more than doubled in the seven-year period from 2002 to 2008 (US DOE 2009). During the first five years of this period, the quantity of vehicle-kilometers traveled increased, and only a slow shift towards more fuel-efficient motor vehicles was seen (Krauss et al. 2007, US DOT 2008). However, during the last few years of this period of rising fuel prices, US consumers increasingly shifted to smaller, lighter, and more fuel-efficient vehicles, while at the same time reducing the quantity of vehicle-kilometers traveled (Vlasic 2008). In fact, December 2008 represented the fourteenth consecutive month in which the vehicle-miles traveled for the month were lower than for the same month in the preceding year (US DOT 2009). If these trends in both the efficiency and quantity of US motor vehicle travel continue, an overall reduction in resource consumption will be realized. However, it remains to be seen how long these market-driven price pressures will continue.

While the price pressures in the cases of US airline passenger travel and US motor vehicle travel came from market forces, other price pressures may need to be legislated, perhaps through revised tax policies. Such an approach is by no means straightforward, but may prove to be an effective approach to reducing resource consumption (Portney et al. 2003). In such a scenario, the size of the price increase does play an important role, both in terms of political feasibility and in terms of effect. For cases in which considerable price increases may be necessary, efficiency mandates may prove to be the more politically-feasible approach (Hughes et al. 2006).

Updates

In order to continue to realize reductions in resource consumption over the long term, it appears that both efficiency mandates and price pressures should be updated regularly. Without constant updating, the rate of efficiency gains will revert back to previous levels, and old dynamics may return. For example, in the case of US motor vehicle travel, the failure to update past efficiency mandates, along with falling motor fuel prices, reversed a trend towards increasing rates of efficiency improvement. Instead, the old dynamics returned, with average annual quantity growth outpacing average annual efficiency improvements by a sizeable margin. On the other hand, in the case of US residential refrigeration, continually-updated efficiency mandates eventually led to a reduction in resource consumption. In the case of price mechanisms, the increases in the rate of efficiency improvement in passenger air travel during periods of increasing fuel prices, and the decreases in the rate of efficiency improvement during periods of decreasing fuel prices, also seem to suggest the importance of continually applying price pressures.

Conclusion

Historically, past efficiency improvements have generally not proven to be successful in reducing humankind's overall consumption of energy resources. Of the over 75 decades examined across ten activities, only a handful of decades had rates of efficiency improvement that matched or exceeded rates of quantity increase. In these cases, efficiency mandates, price pressures, and industry upheaval contributed to these periods of stabilized or decreased resource consumption. Based upon these historical cases, it does appear that efficiency mandates and price pressures, when applied under appropriate circumstances, may prove effective in reducing resource consumption. However, efficiency improvements without external pressures or mandates, rarely appear to lead to reductions in resource consumption.

It seems that much of the debate over the effectiveness of efficiency improvements in reducing resource consumption comes down to a matter of system boundaries. To engineers, who generally draw their system boundaries at the level of an individual product or process, the beneficial effects of efficiency improvements on resource consumption seem clear. However, to economists, who generally draw their system boundaries at the level of the society or the economy as a whole, the beneficial effects of efficiency improvements on resource consumption is much less clear. Khazzom captures this issue of system boundaries with the succinct comment,

> "For the laboratory engineer, a 3-percent improvement in efficiency will always mean, as it should, a 3-percent reduction in energy, since the engineers's (sic) basic assumption is that the appliance will be used to derive the same amount of service as before. But this result cannot be extended mechanically from the

> laboratory to society. Consumers cannot be assumed to be oblivious to the economic consequences of changing efficiency.” (Khazzom 1980).

As engineers, it is critical to understand how product- and process-level efficiency improvements play out in the larger system. While working on such efficiency improvements is worthwhile from an economic and social perspective, it is not necessarily worthwhile from a resource consumption perspective. Instead, improvements in efficiency can in some cases simply lead to larger quantities of goods and services, and greater resource consumption. While engineers should continue to pursue efficiency improvements, such improvements will need to be combined with appropriate conditions or policies in order to realize reductions in resource consumption.

The true message for engineers and others who encourage efficiency-based solutions to our environmental problems is that product- and process-level efficiency improvements, in the absence of external pressures or mandates, do not equate to system-level reductions in resource consumption. Thus, improving efficiency, by itself, should not be thought of as an environmental goal.

Supporting Documentation - Appendix A

Figures A1 through A10 show resource consumption over time for the activities shown in Figures 1 through 10.

FIGURE A1: Resources Consumed (*R*) in Pig Iron Production (World) [a]

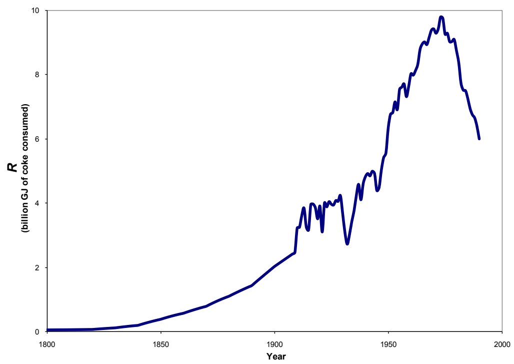


FIGURE A2: Resources Consumed (*R*) in Primary Aluminum Production (World) [b]

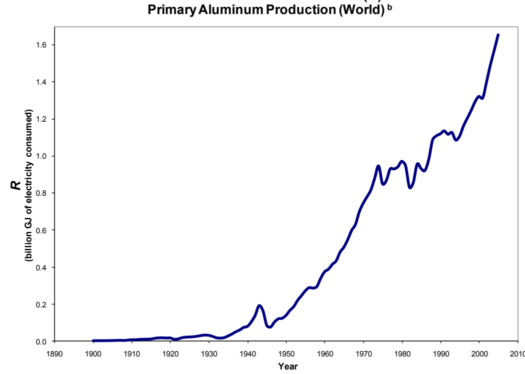


FIGURE A3: Resources Consumed (*R*) in Nitrogen Fertilizer Production (World) [c]

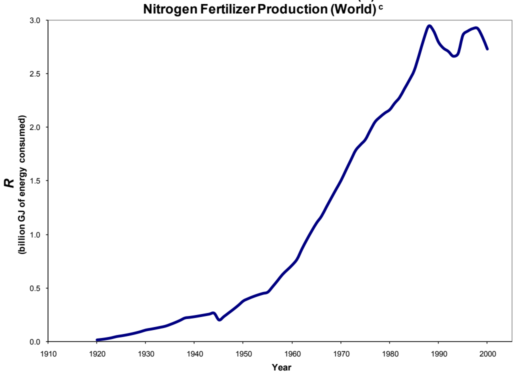


FIGURE A4: Resources Consumed (*R*) in Electricity Generation from Coal (US data) [d]

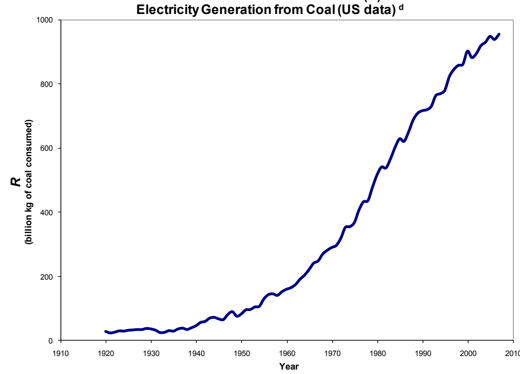


FIGURE A5: Resources Consumed (*R*) in Electricity Generation from Oil (US data) [d]

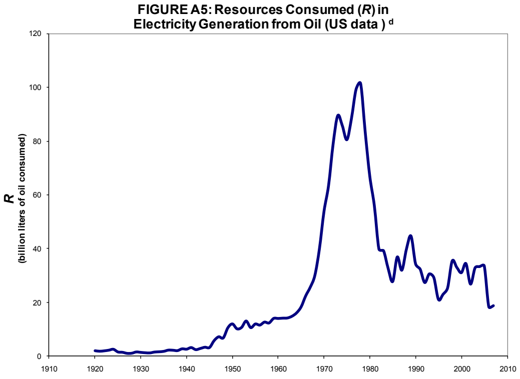


FIGURE A6: Resources Consumed (*R*) in Electricity Generation from Natural Gas (US data) [d]

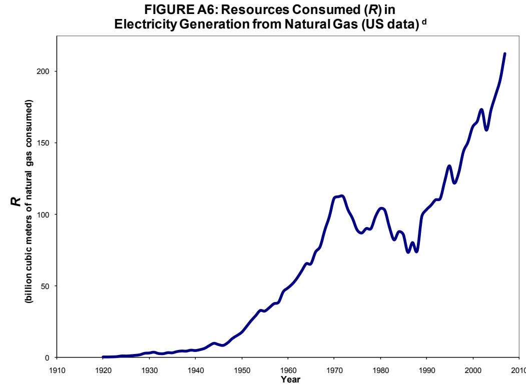


FIGURE A7: Resources Consumed (*R*) in Freight Rail Travel (US Class I railroads) [e]

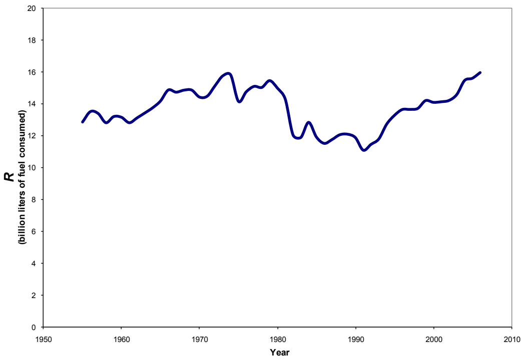


FIGURE A8: Resources Consumed (*R*) in Passenger Air Travel (US airlines) [f]

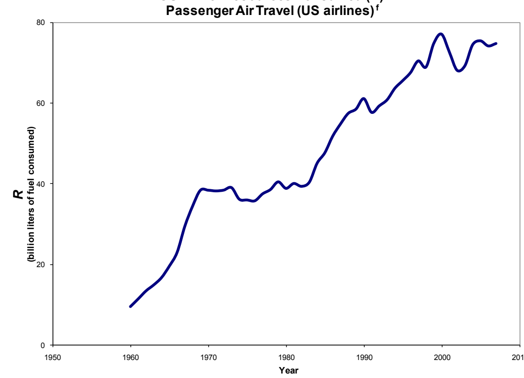


FIGURE A9: Resources Consumed (*R*) in Motor Vehicle Travel (US data) [g]

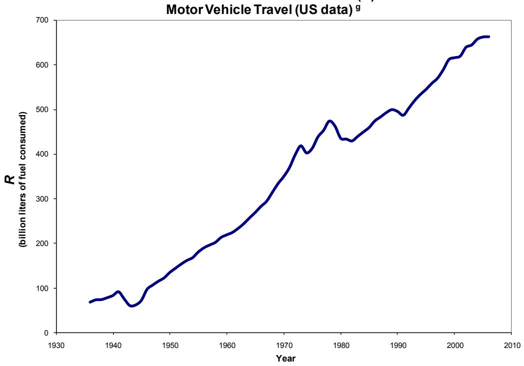
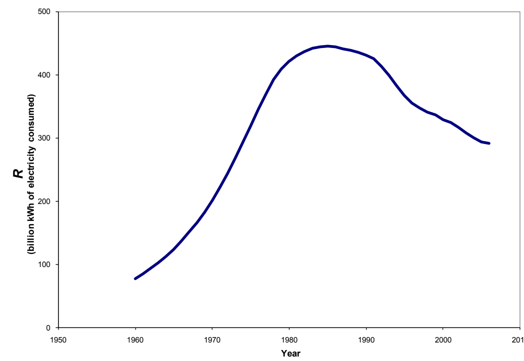


FIGURE A10: Resources Consumed (*R*) in Refrigeration [h]



References

Air Transport Association (ATA), 2007. Economics & Energy, Finance, Quarterly Cost Index: U.S. Passenger Airlines. Available online at http://www.airlines.org/economics/finance/Cost+Index.htm. (Accessed February 27, 2007.)

Anastas, P.T. and J.B. Zimmerman, 2003. Design Through the 12 Principles of Green Engineering. *Environmental Science and Technology* 37(5): 94A-101A.

Ang, B.W. and F.Q. Zhang, 2000. A survey of index decomposition analysis in energy and environmental studies. *Energy* 25(12): 1149-1176.

Association of American Railroads (AAR), 1965. Railroad Transportation, A Statistical Record, 1921-1963. Washington, D.C., April 1965.

Association of American Railroads (AAR), 1983. Railroad Facts, 1983 Edition. Washington, D.C., September 1983.

Association of American Railroads (AAR), 2007. Railroad Facts, 2007 Edition. Washington, D.C., November 2007.

Argote, L. and D. Epple, 1990. Learning Curves in Manufacturing. *Science* 247: 920-924.

Ayres, R.U., L.W. Ayres, and B. Warr, 2003. Exergy, power and work in the US economy, 1900-1998. *Energy* 28(3): 219-273.

Ayres, R.U. and B. Warr, 2005. Accounting for growth: the role of physical work. *Structural Change and Economic Dynamics* 16(2): 181-209.

Bazargan, M., 2004. Airline Operations and Scheduling. Aldershot, Hampshire, UK: Ashgate Publishing, Limited.

Bentzen, J., 2004. Estimating the rebound effect in the US manufacturing energy consumption. *Energy Economics* 26(1): 123-134.

Berkhout, P.H.G., J.C. Muskens, and J.W. Velthuijsen, 2000. Defining the rebound effect. *Energy Policy* 28(6-7): 425-432.

Birol, F. and J.H. Keppler, 2000. Prices, technology development and the rebound effect. Energy Policy 28(6-7): 457-469.

Braeutigan, R.R., 1993. Consequences of Regulatory Reform in the American Railroad Industry. *Southern Economic Journal* 59(3): 468-480.

Brooks, L., 1990. The greenhouse effect: the fallacies in the energy efficiency solution. *Energy Policy* 18(2):199-201.

Brooks, L., 1992. Energy efficiency and economic fallacies: a reply. *Energy Policy* 20(5): 390-392.

Brooks, L., 2000. Energy efficiency fallacies revisited. *Energy Policy* 28(6-7): 355-366.

Business Week, 1984. Can the Rails Stay Lean and Profitable? *Business Week*, May 7, 1984, pp. 72.

Cleveland, C.J. and M. Ruth, 1998. Indicators of Dematerialization and the Materials Intensity of Use. *Journal of Industrial Ecology* 2(3): 15-50.

Considine, T.J. 1991.Economic and Technological Determinants of the Material Intensity of Use. *Land Economics* 67(1): 99-115.

Dahlström, K. and P. Ekins, 2005. Eco-efficiency Trends in the UK Steel and Aluminum Industries: Differences between Resource Efficiency and Resource Productivity. *Journal of Industrial Ecology* 9(4): 171-188.

de Beer, J., E. Worrell, and K. Blok, 1998. Future Technologies for Energy-Efficient Iron and Steel Making. *Annual Review of Energy and the Environment* 23: 123-205.

DeSimone, L.D. and F. Popoff, 1997. Eco-Efficiency: The Business Link to Sustainable Development. Cambridge, Massachusetts, USA: The MIT Press.

Duke, J., D. Litz, and L. Usher, 1992. Multifactor productivity in railroad transportation. *Monthly Labor Review* 115(8): 49-58.

Dybkjaer, I., 1995. “Ammonia Production Processes” in Ammonia: Catalysis and Manufacture, ed. A. Nielsen. Berlin, Germany: Springer-Verlag.

Economist, 2008. Airline Mergers: Trouble in the Air. *The Economist*, April 17, 2008. Available online at http://www.economist.com/business/displaystory.cfm?story_id=11058463. (Accessed August 9, 2008.)

Ehrenfeld, J.R., 2005. Eco-efficiency: Philosophy, Theory, and Tools. *Journal of Industrial Ecology* 9(4): 6-8.

Ehrlich, P.R. and J.P. Holdren, 1972. Critique: One Dimensional Ecology. *Bulletin of the Atomic Scientists* 28(5): 16, 18-27.

Ellerman, A.D., P.L. Joskow, R. Schmalensee, J.P. Montero, and E.M. Bailey, 2000. Markets for Clean Air: The U.S. Acid Rain Program. Cambridge, UK: Cambridge University Press.

Fenton, M.D., 2005. Mineral Commodity Profiles – Iron and Steel. United States Geological Survey Open-File Report 2005-1254. Available online at http://pubs.usgs.gov/of/2005/1254/. (Accessed August 10, 2008.)

Fiksel, J., 1996. “Conceptual Principles of DFE” and “Practical DFE Guidelines” in Design for Environment: Creating Eco-Efficient Products and Processes, ed. J. Fiksel. New York, New York, USA: McGraw-Hill.

Flint, J., 1986. Here Come the Truckbusters: Railroads Come Back into Favor. *Forbes*, June 30, 1986: 86.

Foster, R.N., 1986. Innovation: The Attacker's Advantage. New York, New York, USA: Summit Books.

Gellar, H., 1995. "National Appliance Efficiency Standards: Cost-Effective Federal Regulations," American Council for an Energy-Efficient Economy. Available online at http://www.aceee.org/pubs/a951.htm. (Accessed February 2, 2007.)

Graedel, T. E. and B.R. Allenby, 1998. Design for Environment. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Graedel, T.E. and B.R. Allenby, 2003. Industrial Ecology, Second Edition. Upper Saddle River, New Jersey, USA: Pearson Education, Inc.

Greening, L.A., D.L. Greene, and C. Difiglio, 2000. Energy efficiency and consumption – the rebound effect – a survey. *Energy Policy* 28(6-7): 389-401.

Grubb, M.J., 1990. Energy Efficiency and Economic Fallacies. *Energy Policy* 18(8): 783-785.

Grubb, M.J., 1992. Reply to Brookes. *Energy Policy* 20(5): 392-393.

Grübler, A., 1998. Technology and Global Change. Cambridge, UK: Cambridge University Press.

Heimlich, J., 2007. "U.S. Airline: Operating in an Era of High Jet Fuel Prices." Presentation by John Heimlich, Vice President and Chief Economist, Air Transport Association of America, Inc. January 24, 2007. Available online at http://www.airlines.org/NR/rdonlyres/73AADEC2-D5A2-4169-B590-1EE83A747CDA/0/Airlines_Fuel.pdf. (Accessed February 27, 2007.)

Herring, H., 1998. Does Energy Efficiency Save Energy: The Economists Debate. Energy and Environment Research Unit Report No. 074, July 1998. Available online at http://technology.open.ac.uk/eeru/staff/horace/hh3.htm. (Accessed February 2, 2007.)

Herring, H., 2006. Energy Efficiency – a critical view. *Energy* 31(1): 10-20.

Herring, H., 2007. Visiting Research Fellow, Energy and Environment Research Unit, The Open University, Milton Keynes, UK. Personal communication, April 30, 2007.

Hertwich, E.G., 2005. Consumption and the Rebound Effect: An Industrial Ecology Perspective. *Journal of Industrial Ecology* 9(1-2): 85-98.

Hirsh, R.F., 1999. Power Loss: The Origins of Deregulation and Restructuring in the American Electric Utility System. Cambridge, Massachusetts, USA: The MIT Press.

Hoekstra, R. and J.C.J.M. van den Bergh, 2002. Structural Decomposition Analysis of Physical Flows in the Economy. *Environmental and Resource Economics* 23(3): 357-378.

Holusha, J., 1989. Locomotives in High Gear Again. *New York Times*, April 5, 1989.

Houston Chronicle, 1986. Computerized Locomotive Continue Picking Up Steam. *Houston Chronicle*, June 29, 1986.

Hudson, R. and D. Sadler, 1989. The International Steel Industry: Restructuring, state policies and localities. New York, New York, USA: Routledge.

Hughes, J.E., C.R. Knittel, D. Sperling, 2006. Evidence of a Shift in the Short-Run Price Elasticity of Gasoline Demand. National Bureau of Economic Research Working Paper No. 12530, September 2006. Available online at http://www.nber.org/papers/w12530. (Accessed April 12, 2007.)

Huppes, G. and M. Ishikawa, 2005. Eco-efficiency and Its Terminology. *Journal of Industrial Ecology* 9(4): 43-46.

ICF Consulting (ICF), 2005. Assessing the Effects of Freight Movement on Air Quality at the National and Regional Level, Final Report. Prepared for the U.S. Federal Highway Administration, April 2005. Available online at http://www.oregon.gov/ODOT/TD/FREIGHT/docs/publications/federal/FHWAFrtAirQualRep1.pdf. (Accessed February 27, 2007.)

Intergovernmental Panel on Climate Change (IPCC), 1999. Aviation and the Global Atmosphere. Special report, eds. J.E. Penner, D.H. Lister, D.J. Griggs, D.J. Dokken, and M. McFarland. Available online at http://www.grida.no/climate/ipcc/aviation/index.htm. (Accessed May 13, 2007.)

International Energy Agency/Organisation for Economic Co-Operation and Development (IEA/OECD), 2003. Cool Appliances: Policy Strategies for Energy-Efficient Homes. Paris, France: IEA Publications.

Jevons, W.S., 1865. The Coal Question. Reprints of Economic Classics, ed. A.W. Flux, 1965. New York, New York, USA: Augustus M. Kelley.

Joskow, P.L. and N.L. Rose, 1985. The effects of technological change, experience, and environmental regulation on the construction cost of coal-burning generating units. *Rand Journal of Economics* 16(1):1-27

Khazzoom, J.D., 1980. Economic Implications of Mandated Efficiency Standards for Household Appliances. *Energy Journal* 1(4): 21-40.

Khazzoom, J.D., 1982. Response to Besen and Johnson's Comment on "Economic Implications of Mandated Efficiency Standards for Household Appliances". *Energy Journal* 3(1): 117-124.

Khazzoom, J.D., 1987. Energy Savings Resulting from the Adoption of More Efficient Appliances. *Energy Journal* 8(4): 85-89.

Khazzoom, J.D., 1989. Energy Savings Resulting from the Adoption of More Efficient Appliances: A Rejoinder. *Energy Journal* 10(1): 157-166.

Krauss, C., L. Munoz, and N. Schweber, 2007. Drivers Offer a Collective Ho-Hum as Gasoline Prices Soar. *New York Times*, March 30, 2007.

Krueger, A.B., 2005. Why the Tepid Response to Higher Gasoline Prices? *New York Times*, October 13, 2005.

Kruglinski, A., 1993. A thin locomotive lease market is stretched. *Railway Age*, 194(9): 10.

Lee, J.J., S.P. Lukachko, I.A. Waitz, and A. Schafer, 2001. Historical and Future Trends in Aircraft Performance, Cost and Emissions. *Annual Review of Energy and the Environment* 26:167-200.

Lovell, M.C., 2004. Economics with Calculus. Hackensack, New Jersey, USA: World Scientific Publishing Co.

Lovins, A.B., 1988. Energy Savings Resulting from the Adoption of More Efficient Appliances: Another View. *Energy Journal* 9(2): 155-162.

Mangum, G.L., S.Y. Kim, and S.B. Tallman, 1996. Transnational Marriages in the Steel Industry: Experiences and Lessons for Global Business. Westport, Connecticut, USA: Quorum Books.

McCartney, S. and S. Carey, 2003. Flight Plans: Shifts at Big Airlines Promise to Change the Industry's Course – Cuts at United and American Will Increase the Pressure on Their Smaller Rivals – 'Delicate and Difficult Period'. *Wall Street Journal*, April 17, 2003.

McCartney, S., 2006. The Middle Seat: Sparing Fliers Even Higher Airfares; Oil Hedges, Slower Speeds, Weight Reductions Help Carriers Cut Fuel Costs. *Wall Street Journal*, June 6, 2006.

Milne, G. and B. Boardman, 2000. Making cold homes warmer: the effect of energy efficiency improvements in low-income homes. *Energy Policy* 28(6-7): 411-424.

Morrison, S. A., 1984. An Economic Analysis of Aircraft Design. *Journal of Transport Economics and Policy* 18(2): 123-143.

Omaha World-Herald, 1984. Modern Railroads Embrace Computers. *The Omaha World-Herald*, October 11, 1984.

Organisation for Economic Co-Operation and Development (OECD), 1998. Eco-Efficiency. Paris, France: OECD Publications.

Otto, K.N. and K.L. Wood, 2001. Product Design: Techniques in Reverse Engineering and New Product Development. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Pauly, D., W.J. Cook, and P.E. Simmons, 1980. Green Light on the Rails. *Newsweek*, February 25, 1980: 63.

Pauly, D., R. Thomas, E. Ipsen, and F. Maier, 1982. The Railroads Roll Again. *Newsweek*, May 10, 1982: 69.

Perez, E., S. Carey, and S. McCartney, 2003. Large Airlines Swing Profits With Help – Delta, Northwest, Continental Receive Government Aid Amid War-Related Travel Slump. *Wall Street Journal*, July 18, 2003.

Pindyck, R.S. and D.L. Rubinfeld, 2001. Microeconomics, Fifth Edition. Upper Saddle River, New Jersey, USA: Prentice-Hall, Inc.

Portney, P.R., I. Parry, H. Gruenspecht, and W. Harrington. The Economics of Fuel Economy Standards. *Resources for the Future*, November 2003, RFP DP 03-44.

Prada, P., 2008. American Speeds Jet Purchase: Move Is Part of Plan To Replace Old Planes As Fuel Costs Soar. *The Wall Street Journal*, August 14, 2008.

Railway Age, 1990. Fuel Savers: The Payoff. *Railway Age* 191(10): 31-35.

Roberts, M.C., 1988. What caused the slack demand for metals after 1974? *Resources Policy* 14(4): 231-246.

Rose, A. and S. Casler, 1996. Input-output structural decomposition analysis: A critical appraisal. *Economic Systems Research* 8(1): 33-62.

Rosenfeld, A.H., 1999. The Art of Energy Efficiency: Protecting the Environment with Better Technology. *Annual Review of Energy and the Environment* 24: 33-82.

Roy, J., 2000. The rebound effect: some empirical evidence from India. *Energy Policy* 28(6-7): 433-438.

Ruth, M., 1995. Technology change in US iron and steel production. *Resources Policy* 21(3): 199-214.

Ruttan, V.W., 2001. Technology, Growth, and Development: An Induced Innovation Perspective. New York, New York, USA: Oxford University Press, Inc.

Saunders, H.D., 1992. The Khazzoom-Brookes Postualte and Neoclassical Growth. *Energy Journal* 13(4): 131-148.

Saunders, H.D., 2000. A view from the macro side: rebound, backfire, and Khazzoom-Brookes. *Energy Policy* 28(6-7): 439-449.

Searle, A.D., 1945. Productivity Changes in Selected Wartime Shipbuilding Programs. *Monthly Labor Review* 61: 1132-1147.

Setaishi, S., 2003. Turbulence in Airline Industry Could Hurt Its Supplier Network. *Wall Street Journal*, April 2, 2003.

Sharkey, J., 2004. Sunday Money: Spending; The Air Travel Forecast: Brisk, With Frequent Squalls. *New York Times*, May 30, 2004.

Shedd, T., 1984. The Little Engine That Does. *Technology Review* 87(2): 60-69.

Smil, V., 1994. Energy in World History. Boulder, Colorado, USA: Westview Press, Inc.

Smil, V., 1999. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, Massachusetts, USA: The MIT Press.

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Cambridge, Massachusetts, USA: The MIT Press.

Smil, V., 2003. Energy at the Crossroads: Global Perspectives and Uncertainties. Cambridge, Massachusetts, USA: The MIT Press.

Smil, V., 2007. "Transforming Energy Techniques." Public lecture at Harvard University, April 12, 2007. The Future of Energy Speaker Series 2006-2007, Harvard University Center for the Environment. Available online at http://environment.harvard.edu/video/future_of_energy/smil/presentation.html. (Accessed May 6, 2007.)

Solow, R.M., 1956. A Contribution to the Theory of Economic Growth. *Quarterly Journal of Economics* 70(1): 65-94.

Sullivan, J.L., R.L. Williams, S. Yester, E. Cobas-Flores, S.T. Chubbs, S.G. Hentges, and S.D. Pomper, 1998. "Life Cycle Inventory of a Generic U.S. Family Sedan Overview of Results USCAR AMP Project." Total Life Cycle Conference and Exposition, Graz, Austria, December 1-3, 1998. Society of Automotive Engineers, Technical Paper 982160.

Stern, D.I., 2004. "Economic Growth and Energy" in Encyclopedia of Energy, Volume 2, ed. C.J. Cleveland. Amsterdam, The Netherlands: Elsevier.

Tamaru, K., 1991. "History of Development of Ammonia Synthesis" in Catalytic Ammonia Synthesis: Fundamentals and Practice, ed. J.R. Jennings. New York, New York, USA: Plenum Press.

Tilton, J., 2002. On Borrowed Time?: Assessing the Threat of Mineral Depletion. Washington, D.C., USA: Resources for the Future.

Time, 1974. Detroit Bucks a Buyer Rebellion. *Time*, December 2, 1974: 35-37.

Tugwell, F., 1988. The Energy Crisis and the American Political Economy: Politics and Markets in the Management of Natural Resources. Stanford, California, USA: Stanford University Press.

Ulrich, K.T. and S.D. Eppinger, 2000. Product Design and Development, Second Edition. Boston, Massachusetts, USA: McGraw Hill.

United States Department of Energy (US DOE), 1993. Residential Energy Consumption Survey (RECS) 1993, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 1997. Residential Energy Consumption Survey (RECS) 1997, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 2001. Residential Energy Consumption Survey (RECS) 2001, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 2004. "History of Federal Appliance Standards," Energy Efficiency and Renewable Energy, Building Technologies Program, Appliances and Commercial Equipment Standards. Available online at http://www.eere.energy.gov/buildings/appliance_standards/history.html. (Accessed February 2, 2007.)

United States Department of Energy (US DOE), 2005. Residential Energy Consumption Survey (RECS) 2005, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed August 10, 2008.)

United States Department of Energy (US DOE), 2009. Annual Energy Review 2008: DOE/EIA-0384(2008), Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/aer/contents.html. (Accessed January 15, 2010.)

United States Department of Transportation, (US DOT), 2009. Traffic Volume Trends, Monthly Report. Federal Highway Administration, Office of Highway Policy Information, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/tvtw/tvtpage.cfm. (Accessed January 15, 2010.)

Vlasic, B., 2008. G.M. Shifts Focus to Small Cars in Sign of Sport Utility Demise. *New York Times*, June 4, 2008.

Waggoner, P.E. and J.H. Ausubel, 2002. A framework for sustainability science: A renovated IPAT identity. *Proceedings of the National Academy of Sciences* 99(12): 7860-7865.

Waggoner, P.E., J.H. Ausubel, and I.K. Wernick, 1996. Lightening the Tread of Population on the Land: American Examples. *Population and Development Review* 22(3): 531-545.

Wald, M.L., 2006. Automakers Use New Technology to Beef Up Muscle, Not Mileage. *New York Times*, March 30, 2006.

Warren, K., 2001. Big Steel: The First Century of the United States Steel Corporation 1901-2001. Pittsburgh, Pennsylvania, USA:University of Pittsburgh Press.

Wernick, I.K., P.E. Waggoner, and J.H. Ausubel, 1997. Searching for Leverage to Conserve Forests: The Industrial Ecology of Wood Products in the United States. *Journal of Industrial Ecology* 1(3): 125-145.

Wilen, J., 2008. Airlines Slow Down Flights to Save on Fuel. USA Today, May 2, 2008. Available online at http://www.usatoday.com/travel/flights/2008-05-02-slow-fuel_N.htm. (Accessed August 9, 2008.)

Williams, W., 1985. Turning a Railroad Around. *New York Times*, January 13, 1985.

Wong, E., 2003. Airlines' Unwanted Fleet Grows in the Desert. *New York Times*, June 7, 2003.

World Business Council for Sustainable Development (WBCSD), 2000. Eco-Efficiency: Creating More Value With Less Impact. Available online at http://www.wbcsd.org/web/publications/eco_efficiency_creating_more_value.pdf. (Accessed February 2, 2007.)

Yamaji, K., R. Matsuhashi, Y. Nagata, and Y. Kaya, 1991. "An Integrated System for CO2/Energy/GNP Analysis: Case Studies on Economic Measures for CO_2 Reduction in Japan" presented at the Workshop on CO_2 Reduction and Removal: Measures for the Next Century, March 19-21, 1991, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Supporting Documentation - Figure References

[a] Pig iron production

Efficiency data:

de Beer, J., E. Worrell, and K. Blok, 1998. Future Technologies for Energy-Efficient Iron and Steel Making. *Annual Review of Energy and the Environment* 23: 123-205.

Smil, V., 1999. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, Massachusetts, USA: The MIT Press.

Quantity data:

1800-1990: Smil, V., 1999. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, Massachusetts, USA: The MIT Press.

1910-2006: United States Geological Survey, 2008. "Iron and Steel statistics," from Historical Statistics for Mineral and Material Commodities in the United States: U.S. Geological Survey Data Series 140, comps. T.D. Kelly and G.R. Matos. Available online at http://minerals.usgs.gov/ds/2005/140/. (Accessed July 26, 2008.)

[b] Aluminum production

Efficiency data:

Choate, W., 2007. "U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits, and New Opportunities" in Aluminum Recycling and Processing for Energy Conservation and Sustainability, ed. J.A.S. Green. Materials Park, Ohio, USA: ASM International.

Atkins, P.R., H.J. Hittner, D. Willoughby, 1990. "Some Energy and Environmental Impacts of Aluminum Usage," from Energy and the Environment in the 21st Century, Conference Proceedings, March 26-28, 1990, eds. J.W. Tester, D.O. Wood, and N.A. Ferrari. Cambridge, Massachusetts, USA: The MIT Press.

Chapman, P.F. and F. Roberts, 1983. Metal Resources and Energy. London, UK: Butterworth and Co Ltd.

Quantity data:

United States Geological Survey, 2007. "Aluminum statistics," from Historical Statistics for Mineral and Material Commodities in the United States: U.S. Geological Survey Data Series 140, comps. T.D. Kelly and G.R. Matos. Available online at http://minerals.usgs.gov/ds/2005/140/. (Accessed July 6, 2008.)

[c] Nitrogen fertilizer production

Efficiency and Quantity data:

Smil, V., 2001. Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. Cambridge, Massachusetts, USA: The MIT Press.

[d] Electricity generation

Efficiency and Quantity data:

1920-1970 data: United States Bureau of the Census, 1997. Historical Statistics of the United States, Colonial Times to 1970, Electronic edition, eds. S.B. Carter, et al. [machine-readable data file]. Cambridge, UK: Cambridge University Press.

1949-2007 data: United States Department of Energy, 2008. Annual Energy Review 2007: DOE/EIA-0384(2007), Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/aer/contents.html. (Accessed July 6, 2008.)

[e] Freight rail travel

Quantity data:

1962-1964: Association of American Railroads, 1973. Yearbook of Railroad Facts, 1973 Edition. Washington, D.C., 1973.

1965-1978: Association of American Railroads, 1980. Yearbook of Railroad Facts, 1980 Edition. Washington, D.C., June 1980.

1979-1988: Association of American Railroads, 1989. Railroad Facts, 1989 Edition. Washington, D.C., November 1989.

1989: Association of American Railroads, 1999. Railroad Facts, 1999 Edition. Washington, D.C., October 1999.

1990-2005: Association of American Railroads, 2006. Railroad Facts, 2006 Edition. Washington, D.C., November 2006.

2006: Association of American Railroads, 2007. Railroad Facts, 2007 Edition. Washington, D.C., November 2007.

Resource Consumption data:

1962-1971: Association of American Railroads, 1977. Yearbook of Railroad Facts, 1977 Edition. Washington, D.C., 1977.

1972-1978: Association of American Railroads, 1980. Yearbook of Railroad Facts, 1980 Edition. Washington, D.C., June 1980.

1979-1988: Association of American Railroads, 1989. Railroad Facts, 1989 Edition. Washington, D.C., November 1989.

1989: Association of American Railroads, 1999. Railroad Facts, 1999 Edition. Washington, D.C., October 1999.

1990-2005: Association of American Railroads, 2006. Railroad Facts, 2006 Edition. Washington, D.C., November 2006.

2006: Association of American Railroads, 2007. Railroad Facts, 2007 Edition. Washington, D.C., November 2007.

[f] Passenger air travel

Quantity data:

1937-2007: Air Transport Association, 2008. Economics & Energy, Traffic, Annual Traffic and Ops: U.S. Airlines. Available online at http://www.airlines.org/economics/traffic/Annual+US+Traffic.htm. (Accessed July 5, 2008.)

Resource Consumption data:

1961-1976: United States Department of Transportation, 2007. Reference Services, National Transportation Library, Bureau of Transportation Statistics, Research and Innovative Technology Administration. Personal communication, February 13, 2007.

1977-1999: United States Department of Transportation, 2008. Bureau of Transportation Statistics, Programs, Airline Data and Statistics, Airline Fuel Cost and Consumption. Available online at http://www.bts.gov/xml/fuel/report/src/tableversion.xml. (Accessed July 5, 2008.)

2000-2007: United States Department of Transportation, 2008. Bureau of Transportation Statistics, Research and Innovative Technology Administration, Air Carrier Financial: Schedule P-12A. Available online at http://www.transtats.bts.gov/Oneway.asp?Display_Flag=0&Percent_Flag=0. (Accessed July 5, 2008.)

Fuel price data:

1971-2007: Air Transport Association, 2008. Economics & Energy, Finance, Quarterly Cost Index: US Passenger Airlines. Available online at http://www.airlines.org/economics/finance/Cost+Index.htm. (Accessed July 5, 2008.)

United States Department of Labor, 2008. Bureau of Labor Statistics, Consumer Price Index, CPI Tables, Consumer Price Index History Table. Available online at http://www.bls.gov/cpi/#tables. (Accessed August 10, 2008.)

[g] Motor vehicle travel

Efficiency and Quantity data:

1936-1994: United States Department of Transportation, 1997. Highway Statistics Summary to 1995. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://isddc.dot.gov/OLPFiles/FHWA/006654.pdf. (Accessed February 12, 2007.)

1995: United States Department of Transportation, 1997. Highway Statistics 1996. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/1996/index.html. (Accessed February 12, 2007.)

1996: United States Department of Transportation, 1998. Highway Statistics 1997. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs97/hs97page.htm. (Accessed February 12, 2007.)

1997: United States Department of Transportation, 1999. Highway Statistics 1998. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs98/hs98page.htm. (Accessed February 12, 2007.)

1998: United States Department of Transportation, 2000. Highway Statistics 1999. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs99/index.htm. (Accessed February 12, 2007.)

1999: United States Department of Transportation, 2001. Highway Statistics 2000. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs00/index.htm. (Accessed February 12, 2007.)

2000: United States Department of Transportation, 2002. Highway Statistics 2001. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/ohim/hs01/index.htm. (Accessed February 12, 2007.)

2001: United States Department of Transportation, 2003. Highway Statistics 2002. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs02/index.htm. (Accessed February 12, 2007.)

2002: United States Department of Transportation, 2004. Highway Statistics 2003. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs03/index.htm. (Accessed February 12, 2007.)

2003: United States Department of Transportation, 2005. Highway Statistics 2004. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs04/index.htm. (Accessed February 12, 2007.)

2004: United States Department of Transportation, 2006. Highway Statistics 2005. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs05/index.htm. (Accessed July 26, 2008.)

2005-2006: United States Department of Transportation, 2007. Highway Statistics 2006. Federal Highway Administration, Office of Highway Information Management, Washington, D.C., USA. Available online at http://www.fhwa.dot.gov/policy/ohim/hs06/index.htm. (Accessed July 26, 2008.)

Fuel price data:

United States Department of Energy, 2008. Annual Energy Review 2007: DOE/EIA-0384(2007), Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/aer/contents.html. (Accessed August 10, 2008.)

United States Department of Labor, 2008. Bureau of Labor Statistics, Consumer Price Index, CPI Tables, Consumer Price Index History Table. Available online at http://www.bls.gov/cpi/#tables. (Accessed August 10, 2008.)

Corporate Average Fuel Economy (CAFE) data:

United States Department of Transportation, 2008. National Highway Traffic Safety Administration, CAFE Overview – Frequently Asked Questions. Available online at http://www.nhtsa.dot.gov/CARS/rules/CAFE/overview.htm. (Accessed August 28, 2008.)

[h] Refrigeration

Efficiency data:

1947-2000: Rosenfeld, A.H., 1999. The Art of Energy Efficiency: Protecting the Environment with Better Technology. *Annual Review of Energy and the Environment* 24:33-82.

1980-1999: Association of Home Appliance Manufacturers, 2000. Fact Book 2000. Washington, D.C., USA: Association of Home Appliance Manufacturers.

2000-2004: Association of Home Appliance Manufacturers, 2005. Fact Book 2005. Washington, D.C., USA: Association of Home Appliance Manufacturers.

2006: McNary, B., 2008. Memorandum to Bruce Nelson. Energy Consumption Savings Methodology – 2008 Update. July 14, 2008. Available online at http://www.state.mn.us/mn/externalDocs/Commerce/Energy_Star_savings_estimates_121202023954_EnergySavingsEstimates.pdf. (Accessed August 10, 2008.)

Quantity data:

1940: United States Bureau of the Census, United States Census. University of Virginia Library, GeoStat Center: Collections, Historical Census Browser. Available online at http://fisher.lib.virginia.edu/collections/stats/histcensus/. (Accessed February 3, 2007.)

1993: United States Department of Energy, 1993. Residential Energy Consumption Survey (RECS) 1993, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

1997: United States Department of Energy, 1997. Residential Energy Consumption Survey (RECS) 1997, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

2001: United States Department of Energy, 2001. Residential Energy Consumption Survey (RECS) 2001, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

2005: United States Department of Energy, 2005. Residential Energy Consumption Survey (RECS) 2005, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed August 10, 2008.)

Fleet age distribution data:

United States Department of Energy, 1993. Residential Energy Consumption Survey (RECS) 1993, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy, 1997. Residential Energy Consumption Survey (RECS) 1997, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy, 2001. Residential Energy Consumption Survey (RECS) 2001, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed February 2, 2007.)

United States Department of Energy, 2005. Residential Energy Consumption Survey (RECS) 2005, Energy Information Administration. Available online at http://www.eia.doe.gov/emeu/recs/. (Accessed August 10, 2008.)

Notes

1. For the remainder of this paper, the term "efficiency" will refer to eco-efficiency or, more specifically, resource-use efficiency.

2. The efficiency data used in the pig iron analysis come from various countries, including the UK, the US, and Japan. Given that these countries were generally quite technologically advanced at the time data was collected, the efficiency data used here represents some of the most efficient technology available for pig iron smelting at a given time. The average global efficiency would be lower, given the technologies in use in less technologically-advanced countries.

3. The efficiency data for aluminum smelting used here represent the Hall-Heroult process, in which aluminum oxide, produced from bauxite, is reduced, producing aluminum.

4. The Haber-Bosch process is the primary method of nitrogen fertilizer production, in which ammonia is synthesized from nitrogen and hydrogen. The efficiency data used in the nitrogen fertilizer analysis represent the most efficient technology available at a given time.

   The noticeable drop in nitrogen fertilizer production in the late 1980s and early 1990s can be attributed primarily to the decline of the Soviet Union. In 1988, the Soviet Union was the world's largest producer of ammonia, with over 15 billion kilograms of nitrogen produced (Smil 2001). However, by 1996, the former Soviet states combined for only about half of the production quantity of 1988 (Smil 2001).

5. In the case of electricity generation from coal, shown in Figure 4, the efficiency trends demonstrate an extended period of improving efficiency followed by an extended period of slowly declining efficiency. This latter, long downward trend in efficiency is attributable to various factors, including fuel substitution and power plant (in) efficiencies.

   The increased use of low-sulfur bituminous coal provides one likely explanation for the decline in the efficiency of electricity generation from coal. As part of the 1970 Clean Air Act, controls on certain emissions from power plants, including sulfur dioxide, nitrogen oxides, and particulates, were established. Such legislation led to the implementation of various emission reduction strategies at coal-fired power plants, from implementing flue-gas desulfurization units to switching to low-sulfur coal (Ellerman et al. 2000). This low-sulfur coal also had lower heating values, thus resulting in lower overall electricity generation efficiencies, as measured in units of electricity produced per mass of coal consumed. It should be noted that efficiency could have been measured with respect to an environmental load, instead of with respect to resource consumption. For example, measuring efficiency in units of electricity produced per mass of sulfur dioxide emitted, would cause efficiency to increase, not decrease, as a result of the Clean Air Act.

   Another possible explanation for this downturn in efficiency is the plateauing of power plant efficiencies. While the 1970 Clean Air Act established stricter pollution controls on power plants, existing power plants were exempt from these new regulations. This resulted in many companies choosing to maintain old power plants that were exempt from these regulations, instead of building new power plants that would be subject to these regulations. This had the effect of locking-in existing equipment and efficiencies. It is also interesting to note that around this same time, the thermal efficiency of steam turbines, a critical component of power plants, was beginning to plateau, after almost a century of improvement (Smil 1999).

6. Figure 5, which plots efficiency and production data for electricity generation from oil in the US, shows large fluctuations in production but relatively steady improvements in efficiency. This variation in production is due to both price and supply volatility for oil, as well as to various policy interventions.

   In the late 1960s, electricity generation from oil increased dramatically, primarily because of low oil prices, but also due to environmental reasons, as oil burns more cleanly than coal. With the oil embargo of 1973, oil prices increased dramatically. However, due to severe shortages in other fuels used for electricity generation, namely natural gas, the use of oil for electricity generation continued well into the 1970s. In 1978, the Powerplant and Industrial Fuel Use Act was passed, restricting the construction of power plants that used oil or natural gas. This, along with the Iranian oil shock of 1979, led to a rapid decline in the production of electricity from oil. Since then, electricity generation from oil in the US has fluctuated considerably, but the general trend has been to move away from the use of oil for this purpose.

7. In the case of electricity generation from natural gas, shown in Figure 6, there are significant fluctuations in production but relatively steady improvements in efficiency. As in the case of electricity generation from oil, this variation in electricity production from natural gas is due to both price and supply volatility for natural gas, as well as to various policy interventions.

   In the 1950s and 1960s, government price regulation of natural gas in the US led to declines in production and increases in demand (Tugwell 1988). This combination brought about severe natural gas shortages in the 1970s. During these times of limited supply, homes and businesses were given priority over electricity generation facilities. Thus, electricity generation from natural gas during the 1970s and into the 1980s was quite volatile. This uncertainty of supply, along with the 1978 Powerplant and Industrial Fuel Use Act, brought about an overall decline in electricity generation from natural gas during the 1970s and 1980s. The repeal of parts of the Powerplant and Industrial Fuel Use Act in 1987, combined with falling natural gas prices, helped to bring about a resurgence in the use of natural gas for electricity generation in the US that has continued to this day.

8. In the US, freight railroads are grouped into three categories – Class I, Class II, and Class III – based on operating revenue. Class I encompasses the railroads with the highest operating revenues. In 2006, the seven Class I railroads in the US accounted for 67% of all US freight rail mileage and 93% of all US freight rail revenue (AAR 2007.).

9. Revenue tonne-kilometer (RTK) is a measure of production for freight railroads. RTK values can be obtained by multiplying the number of revenue-generating tonnes of freight by the distance, in kilometers, that each paid tonne of freight travels. One RTK represents one revenue-generating tonne of freight traveling one kilometer.

Efficiency of freight rail travel is measured in RTKs of freight rail travel per volume of fuel consumed, where the fuel consumed is diesel. While other types of fuel have been used for freight rail travel, by 1960, over 97% of the locomotives used by Class I railroads in the US were diesel (AAR 1965). Since then, diesel has remained the most popular fuel for freight rail.

10. Available seat-kilometer (ASK) is a measure of production or capacity for airlines. ASK values can be obtained by multiplying the number of seats available for passengers by the distance, in kilometers, that each of those seats is flown (Bazargan 2004). One ASK represents one seat traveling one kilometer. ASK is independent of load factor, meaning that it is independent of how many seats on an airplane are occupied.

11. The term "motor vehicle" refers to virtually all vehicles on the road, including passenger cars, motorcycles, buses, and trucks.

12. Vehicle-kilometer is a measure of production for motor vehicles. Vehicle-kilometer values can be obtained by multiplying the number of motor vehicles by the distance, in kilometers, that each vehicle travels. One vehicle-kilometer represents one vehicle traveling one kilometer.

13. The noticeable smoothing of the data in the case of refrigeration is due to both limited data, in the case of quantity data, and fleet averaging, in the case of efficiency data. For annual quantity data, values between limited data points were obtained using a third order polynomial with an r-squared value of approximately 0.99996. The annual efficiency data for refrigeration is a measure of the average efficiency of the refrigerators in service in a given year. This value is obtained by using both the efficiency data for new refrigerators in a given year and data about the age distribution of the refrigerator fleet in a given year (Rosenfeld 1999, US DOE 1993, US DOE 1997, US DOE 2001).

[14] The majority of pig iron produced in the world is used to make steel. Thus, pig iron production and steel production are closely linked. In many applications, substitute materials – including plastics and aluminum – substituted for steel, not iron. However, given the strong link between the two, a decline in steel use led to a decline in pig iron use.

In some industries, such as the automobile industry, the shift away from steel was quite pronounced (Mangum et al. 1996). In 1975, an average US-made automobile contained approximately 75% iron and steel and only about 5% plastics and aluminum (Time 1974). By 1995, an average US-made automobile contained around 65% iron and steel and about 15% plastics and aluminum (Sullivan et al. 1998).

15. Giving rail companies the ability to set their own rates and to shut down unprofitable rail lines had a number of important ramifications. First, the ability to set their own rates made the rail industry much more competitive with trucking, as rail was now able to negotiate individual contracts for each customer (Williams 1985, Flint 1986). This ability to set rates also allowed rail companies to fill trains will low-rate cargo in order to avoid empty mileage, which in some years could account for 40% of total miles (Flint 1986). This reduction in empty mileage helped to improve both profitability and fuel efficiency.

The ability to close unprofitable rail lines allowed companies to discontinue service on less-traveled sections of track, thus reducing operating costs and improving profitability. The closing of rail lines, along with a recession-related equipment surplus in the early 1980s, allowed some older, less-efficient equipment to be removed from service (AAR 1983).

16. The new innovations in rail cars included “piggyback” or “trailer on flat car” (TOFC) trains, in which containers and trailers – and sometimes double-stacked containers and trailers – are carried on flat rail cars (Williams 1985, Flint 1986, Duke et al. 1992). Other changes in equipment, including the introduction of high-efficiency, microprocessor-controlled locomotives, and the use of advanced wheel slip-control systems, also improved fuel efficiency, although such improvements generally take some time to manifest themselves at the fleet level (Shedd 1984, Houston Chronicle 1986). Operationally, in addition to improved train scheduling and routing, changes made by train engineers, including reducing unnecessary braking and reducing acceleration rates, also led to noticeable efficiency improvements (Railway Age 1990, Shedd 1984).

17. While both operational and technological changes can improve fuel efficiency, the time scales over which these improvements are realized can differ greatly. In the case of changes to airframes and engines, the long lifespan of aircraft, typically around 25 years, results in a considerable lag in technology (IPCC 1999, Lee et al. 2001). These long lifespans, along with long development, certification, and production times for airframes and engines, mean that an increased interest in fuel efficiency by the air travel industry may not manifest itself in the aerodynamic and engine efficiency of the aircraft fleet for quite some time. Some have estimated this time delay between initial development and actual impact at the fleet level to be as much as 25 years (Lee et al. 2001.).

    While improvements to airframes and engines take some time to manifest themselves, there are operational changes that can yield more immediate results. Improvements in air traffic management, including reducing air and ground delays, improving flight routing, and, more recently, reducing vertical separation minimums, can lead to considerable increases in fuel efficiency (IPCC 1999, Lee et al. 2001, ICF 2005, McCartney 2006, Heimlich 2007). Other common operational approaches to improve fuel efficiency include reducing aircraft weight by removing unnecessary equipment such as magazines and seat-back phones, and reducing aircraft drag by lowering cruising speeds and implementing stricter repair and maintenance programs (McCartney 2006, Heimlich 2007). Together, these various operational changes can lead to immediate improvements in fuel efficiency. It is important to point out that increasing passenger load factors, a technique that has been employed frequently by airlines in recent years, improves efficiency on a revenue passenger kilometer (RPK) basis, but not on the available seat kilometer (ASK) basis used here. The number of ASKs, multiplied by the passenger load factor, yields the number of RPKs.

18. This period of declining efficiency in the US was due in large part to market demand, as an increasingly affluent post-World War II public demanded larger, more powerful motor vehicles with more accessories (Hirsh 1999).

19. The period of improving efficiency, which began in the mid-1970s, was brought about by both market forces and legislative action. The oil crises of the 1970s introduced gasoline supply concerns and higher gasoline prices to drivers in the US, thereby stimulating consumer interest in improved motor vehicle fuel efficiency. Legislatively, Corporate Average Fuel Economy (CAFE) standards, which, beginning in 1978, mandated a minimum average fuel economy for a manufacturer's fleet of vehicles, also drove automakers to improve fuel efficiency. Combined, these factors had a noticeable effect on the efficiency of motor vehicle travel in the US.

20. In the US, starting in the 1970s, states, in particular California, began mandating minimum efficiency requirements on new household appliances (Gellar 1995). These requirements were updated over time, ensuring that efficiency improvements would continue. In 1987, with a patchwork of state requirements already in place, the National Appliance Energy Conservation Act created federal minimum efficiency requirements for residential appliances, including refrigerators (US DOE 2004). Since then, the efficiency standards for refrigerators have been updated multiple times, ensuring that efficiency improvements continued (IEA/OECD 2003).

21. The quantity tracked in this activity, namely hours of refrigeration, is obtained by multiplying the number of refrigerators in the US by the number of hours in a year. While the number of hours in a year remains constant, the number of residential refrigerators in the US has increased, thus explaining the overall increase in the hours of refrigeration, as seen in Figure 10. Recently, growth in the number of residential refrigerators has outpaced growth in the number of households in the US, as American households have increasingly added second refrigerators. From 1993 to 2005, the percentage of US households with two or more refrigerators has increased from just under 15% in 1993, to over 22% in 2005 (US DOE 1993, US DOE 1997, US DOE 2001, US DOE 2005).

22. Prior to the development of the Haber-Bosch process, the industrial methods available for producing nitrogen included the fixation of atmospheric nitrogen using calcium carbide at high temperatures to produce calcium cyanamide ($CaC_2 + N_2 \rightarrow CaCN_2 + C$), and the fixation of atmospheric nitrogen by electrical discharge to produce nitric oxide ($N_2 + O_2 \leftrightarrow 2NO$) (Tamaru 1991, Smil 2001).

23 The improvements in efficiency resulting from learning can be quite impressive. For example, in the case of Liberty ships built for the US and its allies for use in World War II, between December 1941, the delivery date of the first Liberty ship, and December 1942, the average number of man-hours per ship decreased 45% and the average days per ship decreased 76% (Searle 1945). Overall, across ten different shipyards, the average number of labor hours required to build a Liberty ship decreased by around 20% for each doubling of output (Ibid.).

24. In some cases, the planes that are the most costly to operate are not those with the worst fuel efficiency, but instead the planes that are of a different make or model from the majority of other planes in an airline's fleet (Wong 2003). In general, large cost savings can be realized, both in operation and in maintenance, by having a limited variety of planes.

25. Vaclav Smil offered his own humorous insights into the benefits of improvements in air travel and, more specifically, improvements in the efficiency of aircraft engines. In a 2007 lecture entitled "Transforming Energy Techniques", Smil commented,

> "These new big gas turbines, these, you know, GE and Rolls Royce things, they are marvels of engineering – much more efficient, much lighter, much more durable. The single most durable machine on this planet. You notice the plane goes, two hours they refuel it, goes back, and keeps doing it for seven months before they even look at the bloody engine. They don't even look at it! The most marvelous machine ever. But what is happening? These old inefficient turbojets. In 1960, who was flying? If somebody was flying, 'Oh, he *flew* somewhere! Amazing! First person in our family who flew somewhere,' right? Now? There is (sic) 78 discount airlines in Western Europe alone really. And people are flying – where is the number one destination in the continent? 45 million people fly to Las Vegas for what, you know, to spend money which they don't have really. This is what the efficient engine has brought us. People frivolously flying into the middle of the desert without any water to spend money which they don't have, really, right. So that's the benefit of efficient engines, ok." (Smil 2007).

26. While the substitution effect always leads to greater consumption, the income effect can lead to either an increase or a decrease in consumption, depending on the type of good. In the case of normal goods, the income effect increases demand; in the case of inferior goods, for which consumption decreases as income increases, the income effect decreases demand. In most cases however, there is an overall increase in consumption, as the substitution effect is typically larger in magnitude than the income effect (Pindyck and Rubinfeld 2001).

27. Although data is difficult to find, it would be interesting to examine overall trends in refrigeration, not just trends in residential refrigeration, as are analyzed here. Given the increase in the US of dining and food service outside the home, the overall quantity of refrigeration, including both the service sector and the residential sector, may have grown at a faster rate than for the residential sector alone (Herring 2007). Significantly faster growth rates in the overall quantity of refrigeration could eclipse the rate of efficiency improvement, thus leading to an overall increase in resource consumption.