Can Efficiency Improvements Reduce Resource Consumption?

A Historical Analysis of Ten Activities

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Abstract

This work explores the historical effectiveness of efficiency improvements in reducing mankind's resource consumption. 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 refrigeration. The data and analyses presented here 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 a sizeable increase in resource consumption across all ten sectors. 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

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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 1998, 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 been pursuing efficiency improvements for centuries yet, during that time, resource consumption has continued to increase. This increase in resource consumption is not surprising, given the growth in population and the rise in 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.

The historical data and analyses presented here examine past trends in efficiency and resource consumption across ten activities. In particular, this work focuses on identifying historical cases in which efficiency improvements have resulted in reductions in resource consumption and, looking forward, what insights those cases provide with regards to leveraging future efficiency improvements to realize reductions in resource consumption.

Background

In framing the relationship between efficiency improvements and resource consumption, the familiar *IPAT* identity can be used. This identity, first developed in the 1970s, is commonly used to help isolate and quantify the multiple factors that contribute to mankind's impact on the earth. The *IPAT* identity disaggregates impact (I) into the product of population (P), affluence (A), and technology (T). It can be written as

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

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 individual aspects of sustainability, 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,

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

where "Quantity" refers to the quantity or level of goods and services provided in a society and "Resources" refers to the amount of resources consumed. In (2), the affluence term from (1) is represented as the product of GDP over Population – which represents per capita income – and Quantity over GDP – which represents the quantity of goods and services provided per unit of income. The technology term from (1) is represented in (2) as the product of Resources over Quantity – which represents the resource intensity of the goods and services provided – and Impact over Resources – which represents the environmental intensity of resource consumption. 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 population and affluence terms in (2) can be combined, yielding

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

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 of (4) 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 resource consumed. This is in fact an eco-efficiency, a ratio of economic value to environmental load (Ehrenfeld 2005). Thus, (4) can be rewritten as

$$Resources = Quantity\ x\ \frac{1}{Resource\ Productivity} \quad , \tag{5}$$

or

$$Resources = Quantity\ x\ \frac{1}{Eco-efficiency} \quad . \tag{6}$$

From (6) 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

$$\frac{\Delta e}{e} > \frac{\Delta Q}{Q} > 0 \quad , \tag{7}$$

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

Previous Work

Historical trends in efficiency have been tracked and analyzed by others. A number of works by Smil and Ayres et al. provide in-depth analyses of efficiency improvements for a broad range of activities (Smil 1994, Smil 1999, Smil 2003, Ayres et al. 2003, Ayres and Warr 2005). While these works do sometimes frame these efficiency improvements in the larger context of economic growth and development, they do not directly compare the rate of efficiency improvements with the rate of quantity increases.

The overall approach taken here, which isolates and analyzes the critical factors driving resource consumption, draws from prior works using decomposition analysis. Works by Waggoner, Wernick, and Ausubel, utilize similar decomposition approaches to disaggregate the critical factors contributing to various metrics, including 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, which 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 (6), 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, (7) 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 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.

It should be noted that for each of the ten activities analyzed, the boundaries of the analysis can be quite varied. Geographically, some activities are analyzed from a global perspective, while others include only US data. In general, for goods and services that are traded on global markets, including pig iron, aluminum, and nitrogen fertilizer, global data was used. For goods and services with geographic limits, such as motor vehicle travel and refrigeration, US data was used. Perhaps the larger difference in analyses stems from the system boundaries established for each activity. For some activities, such as aluminum production, the boundary is drawn at the process-level, meaning that only the technological improvements affecting a single process are included. For other activities analyzed here, 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. It will be shown that despite the varied boundaries 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 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 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.[14] 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]

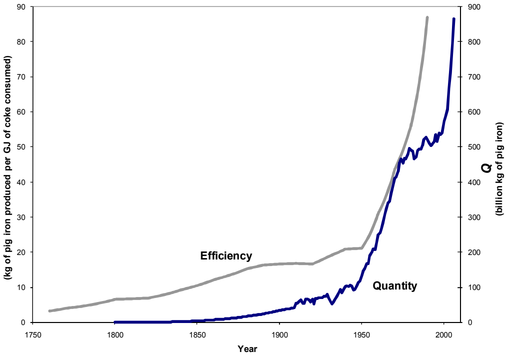


FIGURE 2: Primary Aluminum Production (*Q*) and the Efficiency of Aluminum Smelting (*e*) (World) [b]

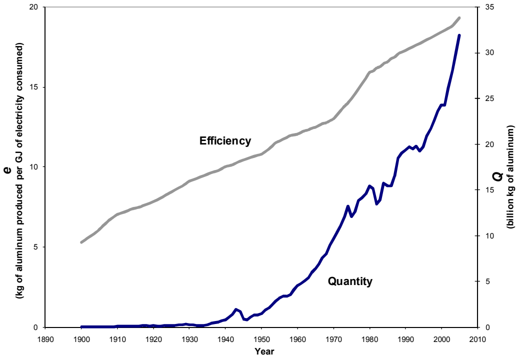


FIGURE 3: Nitrogen Fertilizer Production (*Q*) and the Efficiency of the Haber-Bosch Process (*e*) (World) [c]

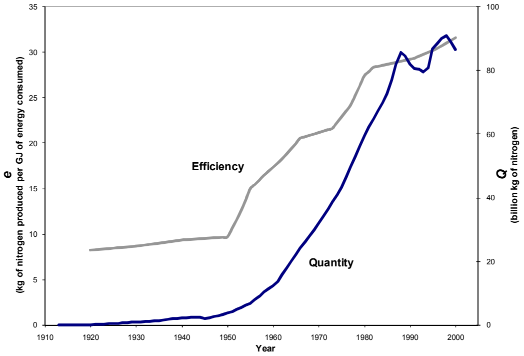


FIGURE 4: Electricity Generation from Coal (*Q*) and the Efficiency of Electricity Generation from Coal (*e*) (US) [d]

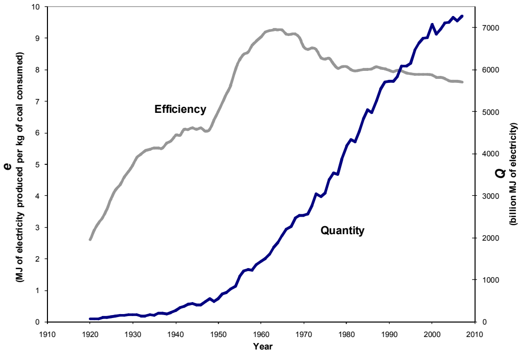


FIGURE 5: Electricity Generation from Oil (*Q*) and the Efficiency of Electricity Generation from Oil (e) (US) [d]

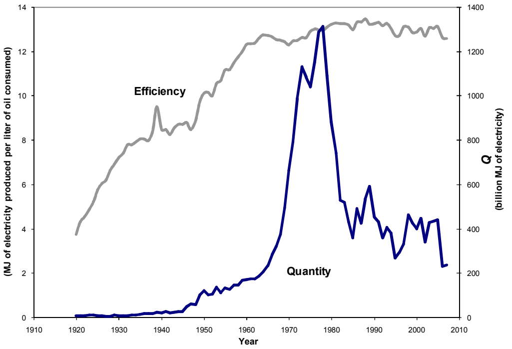


FIGURE 6: Electricity Generation from Natural Gas (*Q*) and the Efficiency of Electricity Generation from Natural Gas (e) (US) [d]

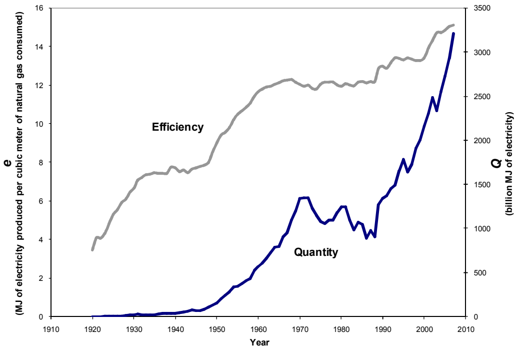


FIGURE 7: Freight Rail Travel (*Q*) and the Efficiency of Freight Rail Travel (e) (US Class I Railroads) [e]

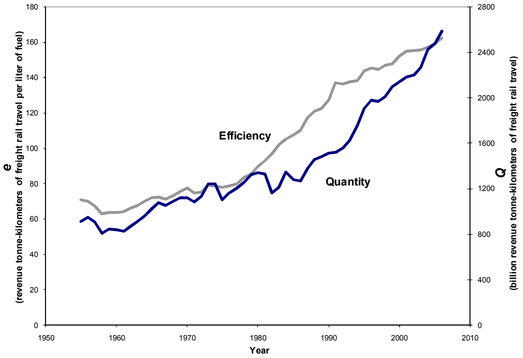


FIGURE 8: Passenger Air Travel (*Q*) and the Efficiency of Passenger Air Travel (e) (US airlines) [f]

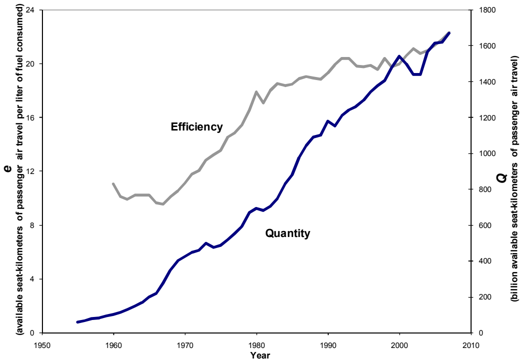


FIGURE 9: Motor Vehicle Travel (*Q*) and the Efficiency of Motor Vehicle Travel (e) (US) [g]

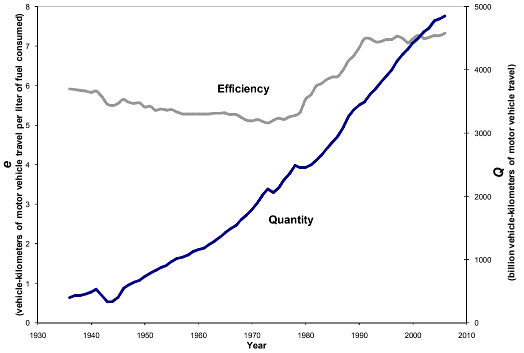


FIGURE 10: Refrigeration (*Q*) and the Efficiency of Refrigeration (e) (US) [h]

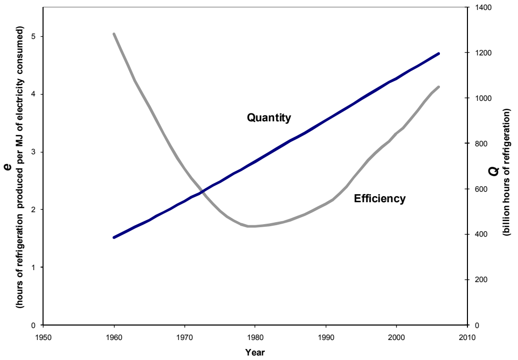


Table 1 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in quantity, $\Delta Q/Q$, for the ten activities analyzed in Figures 1 through 10. Positive values for changes in efficiency indicate efficiency improvements, while positive values for changes in 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, (7) was not satisfied. Thus, despite significant improvements in efficiency, the resources consumed by each of these activities, as calculated using (6), has increased. Figures in Appendix A clearly show this overall increase in resource consumption over the time periods analyzed here.

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
Aluminum	1900-2005	1.2%	9.8%	7.9
Nitrogen Fertilizer	1920-2000	1.0%	8.8%	8.9
Electricity				
from Coal	1920-2007	1.3%	5.7%	4.5
from Oil	1920-2007	1.5%	6.2%	4.2
from Natural Gas	1920-2007	1.8%	9.6%	5.5
Freight Rail Travel	1960-2006	2.0%	2.5%	1.2
Passenger Air Travel	1960-2007	1.3%	6.3%	4.9
Motor Vehicle Travel	1940-2006	0.3%	3.8%	11.0
Refrigeration	1960-2006	-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 over different time periods. 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 (7) is not satisfied, while points below this line represent periods of decreasing resource consumption, where (7) is satisfied. From Figure 11, it is clear that in each of the ten cases examined above, (7) is not satisfied.

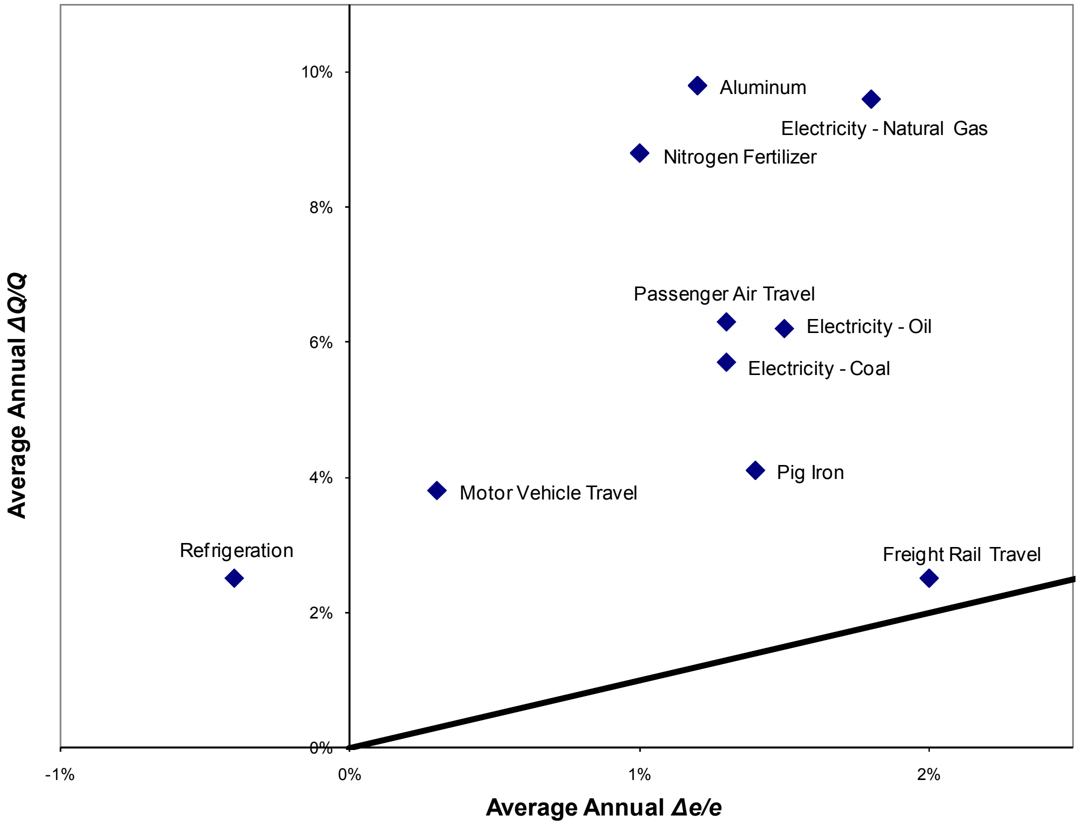


Figure 11: Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for ten activities.

The fact that improvements in efficiency have not been able to outpace increases in quantity over the long term is perhaps not surprising. In fact, similar results have been seen in the structural decomposition analysis literature, where quantity effects have generally been found to outpace technological improvements (Hoekstra and van den Bergh 2002). This inability of past efficiency improvements to reduce resource consumption does bring into question the potential for future efficiency improvements to reduce resource consumption.

Decade-by-Decade Analysis

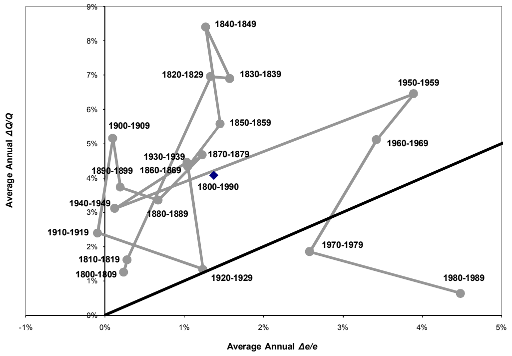
While the long time periods presented above may appear to show little hope for efficiency improvements as a means of reducing resource consumption, a decade-by-decade analysis of these activities reveals a few time periods in which improvements in efficiency did outpace increases in the quantity of goods 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 $\Delta Q/Q$
Pig Iron	1800-1990	1.4%	4.1%
	1800-1809	0.2%	1.3%
	1810-1819	0.3%	1.6%
	1820-1829	1.3%	7.0%
	1830-1839	1.6%	6.9%
	1840-1849	1.3%	8.4%
	1850-1859	1.5%	5.6%
	1860-1869	1.0%	4.3%
	1870-1879	1.2%	4.7%
	1880-1889	0.7%	3.4%
	1890-1899	0.2%	3.7%
	1900-1909	0.1%	5.2%
	1910-1919	-0.1%	2.4%
	1920-1929	1.2%	1.3%
	1930-1939	1.0%	4.5%
	1940-1949	0.1%	3.1%
	1950-1959	3.9%	6.5%
	1960-1969	3.4%	5.1%
	1970-1979	2.6%	1.9%
	1980-1989	4.5%	0.6%

Table 2: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for 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 pig iron data from Table 2. As in Figure 11, the dark diagonal line in Figures 12 represents a line of constant resource consumption, where 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 (7) is not satisfied, while points below this line represent periods of decreasing resource consumption, where (7) is satisfied.

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, pig iron 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.

The rapid improvements in efficiency and the slower-than-usual increases in quantity were driven by a number of factors. Technologically, improvements such as the use of pelletized ore, an increase 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). On the quantity side, this period proved to be a turbulent time for the iron and steel industry, marked by rising petroleum costs, 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 other factors, including the greater availability of substitute materials such as plastics and aluminum, as well as a slowdown in infrastructure building in developed countries, also accounted for the slower average annual increases in pig iron quantity during this period (Hudson and Sadler 1989, Mangum et al. 1996, Warren 2001).[15]

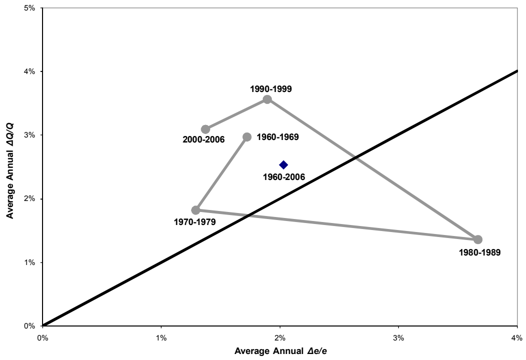
Another activity in which, on a decade-by-decade basis, improvements in efficiency outpaced increases in quantity is freight rail travel. The data for freight rail travel by US Class I railroads, over five time periods from 1960 to 2006, is shown in Table 3.

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

Table 3: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for 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.

Figures 13 plots the decade-by-decade data for freight rail travel from Table 3. As in previous figures, the dark diagonal line in Figure 13 represents a line of constant resource consumption, where 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 (7) is not satisfied, while points below this line represent periods of decreasing resource consumption, where (7) is satisfied.

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, 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).[16] 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).[17] 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).[18]

While the other transportation activities included in Table 1 and Figure 11, namely passenger air travel and motor vehicle travel, never experience a decade in which average annual improvements in efficiency outpace 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.

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

Table 4: Average annual $\Delta e/e$ and average annual $\Delta Q/Q$ for 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 plots the decade-by-decade data from Table 4. As before, the dark diagonal line in Figure 14 represents a line of constant resource consumption, where the average annual $\Delta e/e$ is equal to the average annual $\Delta Q/Q$.

FIGURE 14: Average Annual *ΔQ/Q* versus Average Annual *Δe/e* for Passenger Air Travel (US airlines) [f]

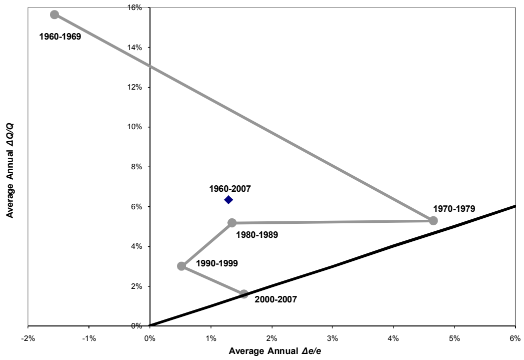
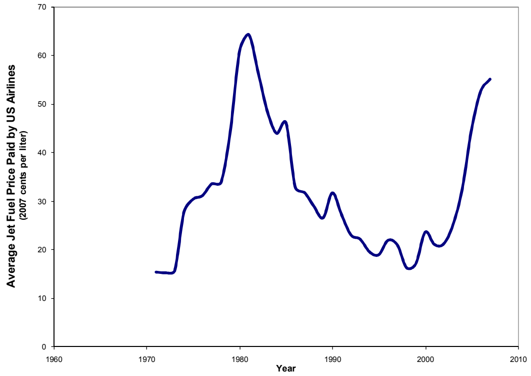


FIGURE 15: Historical Jet Fuel Prices [f]



While 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 (7). 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 for the balance of this decade, remains to be seen. However, given rising 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).[19]

The other period in which passenger air travel nearly satisfied (7) 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 motor vehicle travel. 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 (7) was satisfied.

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

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 plots the decade-by-decade data from Table 5. Again, the dark diagonal line in Figure 16 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.

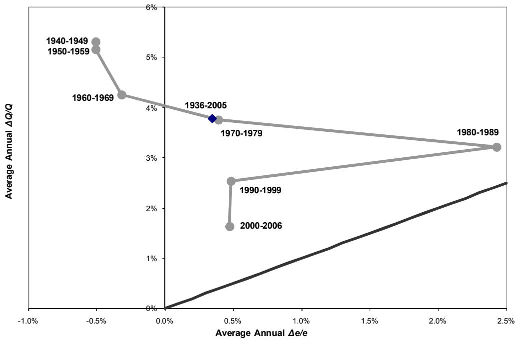


FIGURE 16: Average Annual $\Delta Q/Q$ versus Average Annual $\Delta e/e$ for Motor Vehicle Travel (US data) [g]

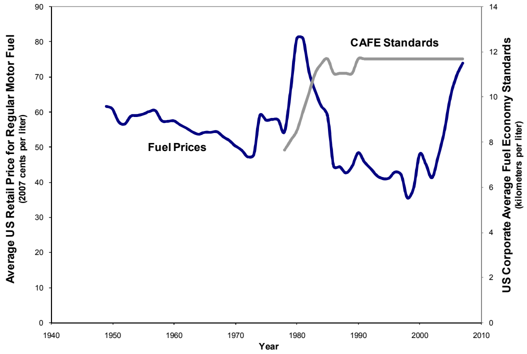


FIGURE 17: Historical Motor Fuel Prices and Corporate Average Fuel Economy (CAFE) Standards [g]

Over the almost seven decades shown in Table 5 and Figure 16, the average annual change in efficiency for motor vehicle travel has varied considerably. From the 1940s through the 1960s, efficiency declined, as motor vehicles became larger and more powerful.[20] 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.[21] 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 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 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 motor vehicle travel could become easier.

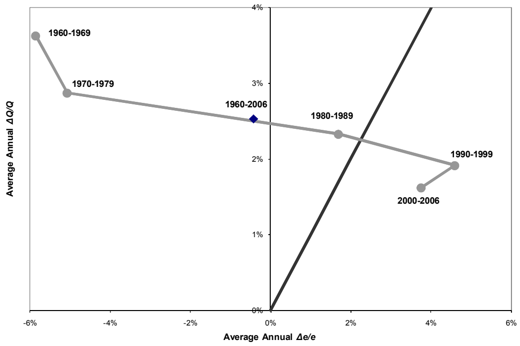
One final case in which improvements in efficiency did outpace increases in quantity on a decade-by-decade basis, is refrigeration. Table 7 summarizes the average annual change in efficiency, $\Delta e/e$, and the average annual change in quantity, $\Delta Q/Q$, for refrigeration, both overall and on a decade-by-decade basis.

Activity	Time Period	Average Annual *Δe/e*	Average Annual *ΔQ/Q*
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%
	1990-1999	4.6%	1.9%
	2000-2006	3.7%	2.5%

Table 7: Average annual *Δe/e* and average annual *ΔQ/Q* for refrigeration on a decade-by-decade basis. The time periods in which average annual *Δe/e* outpaced average annual *ΔQ/Q* are highlighted.

Figure 18 plots the decade-by-decade data from Table 7. The dark diagonal line again represents a line of constant resource consumption.

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 impact. 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.[22] 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.[23]

These decade-by-decade analyses show that in the cases of pig iron, freight rail travel, and refrigeration, decade-long periods did occur in which improvements in efficiency successfully outpaced increases in quantity, meaning that (7) was satisfied and reductions in resource consumption were realized. Looking forward, it is critical to understand the circumstances that enabled improvements in efficiency to outpace increases in quantity in these three cases. If these conditions can be identified and recreated, there exists the possibility that future efficiency improvements could also lead to successful reductions in resource consumption.

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 (7).

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 (Otto and Wood 2001). As the technology becomes more widely disseminated and more resources are applied to the problem, a period of rapid improvement ensues (Ibid.). Finally, there is a plateau in performance, as technologies mature and reach their practical and/or thermodynamic limits (Ibid.). 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 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.[24] 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).[25] Through learning, cumulative quantity can drive efficiency; thus, the terms in (7) – quantity and efficiency – are, in this case, 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 two terms in (7) can be positively correlated.

In the case of pig iron, 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 (Ibid.). 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 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.[26] 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 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.

Consumers and Consumer Demand

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.[27] In this work, quantity, as seen in (3), represents the product of population and affluence. Thus, by definition, increases in population and affluence drive increases in quantity.

Changing consumer taste can also play an important role in quantity. For example, in the case of 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.[28]

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 technical 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. As early as 1865, W. Stanley 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 (Ibid.). In both cases, exactly how much more is consumed depends on the price elasticity of demand for these goods and services.[29] 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 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% (Ibid.). 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 (7) are not independent. Thus, in order to reduce resource consumption, one cannot simply focus on a single term in (6), but must instead approach this as a system problem.

While it is important to acknowledge that efficiency and quantity are often correlated, it is also critical to identify the circumstances under which efficiency improvements can in fact lead to reductions in resource consumption. If such scenarios can be identified and reproduced, there exists the possibility that future efficiency improvements may lead to reductions in resource consumption.

In looking at the periods of reduced resource consumption presented here, it is apparent that different circumstances drove each case. For pig iron and freight rail travel, the periods of reduced resource consumption corresponded with turbulent times in their respective industries. In the case of pig iron, a weak global economy and volatile fuel prices led to this instability, while in the case of freight rail travel, deregulation led to industry upheaval. For 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 passenger air travel and motor vehicle travel can also be included. For passenger air travel, periods of relatively stable resource consumption corresponded with periods of increasing jet fuel prices. For 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 (7) 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.

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.[30]

Efficiency mandates for other goods and services with little rebound may also prove successful. For example, efficiency mandates on other appliances, including dishwashers and laundry machines, may lead to reductions in resource consumption. Motor vehicle travel, with a direct rebound effect between 10 and 30%, may also represent a case in which efficiency mandates can lead to impact reduction (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 successful. Indeed, past efficiency mandates on motor vehicles 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 (7), and thus to reducing resource consumption.

Price Pressures

Price pressures also appear to be a promising approach to realizing reductions in resource consumption, although the exact effect depends largely on the short-run and long-run price elasticities of demand. In the case of durable goods, which have high short-run price elasticities of demand and lower long-run price elasticities of demand, price increases can lead to sizeable decreases in demand in the short term, but a recovery in demand in the long term. For non-durable goods, which have low short-run price elasticities of demand and higher long-run elasticities of demand, 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 short-term 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 passenger air travel, price pressures, in the form of increased jet fuel prices, 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, the low short-run price elasticity of demand for jet fuel did help to spur efficiency improvements in the longer term.

Using price pressures to reduce resource consumption for other goods and services may also prove successful. For example, in the case of motor vehicle travel, the price elasticity of demand for motor fuel follows that of most non-durable goods. Thus, 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 mid-2001 to mid-2008 (US DOE 2008). During the first five years of this period, the quantity of vehicle-kilometers traveled continued to increase, and only a slow shift towards more fuel-efficient motor vehicles was seen (Krauss et al. 2007, US DOT 2008). This result can be attributed in part to the low short-run price elasticity of demand for motor fuel. In fact, since the late 1970s, the short-run price elasticity of demand for motor fuel has shifted significantly lower, as structural and behavioral changes in society have led to less flexibility with regards to motor fuel price (Hughes et al. 2006). During the past few years of this period of rising fuel prices, it appears that consumers have increasingly shifted to smaller, lighter, and more fuel-efficient vehicles (Vlasic 2008). At the same time, the quantity of vehicle-kilometers traveled has declined, with almost 5 percent fewer vehicle-kilometers traveled in June 2008 than in June 2007; in fact, June 2008 represented the eighth consecutive month in which the vehicle-miles traveled for the month were lower than for the same month in the preceding year (US DOT 2008). If these trends in both the efficiency of motor vehicle travel and in the quantity of 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 airline passenger travel and motor vehicle travel came from market forces, other price pressures may need to be legislated, perhaps through taxation. Although introducing new taxes is politically difficult, it may prove to be an effective approach to reducing impact. Of course, the size of the price increase does play an important role, both in terms of political feasibility and in terms of effect. Thus, much care must be taken to apply appropriate price pressures to allow for reduction in resource consumption, without hindering economic growth. 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 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 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 mankind's overall consumption of resources. Of the over 75 decades examined across ten activities, only a handful of decades had rates of efficiency improvement that exceeded or matched rates of quantity increase. In these cases, efficiency mandates, price pressures, and industry upheaval contributed to these periods of decreased or stabilized 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, as the many links between efficiency and quantity have shown, 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 may 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.

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]

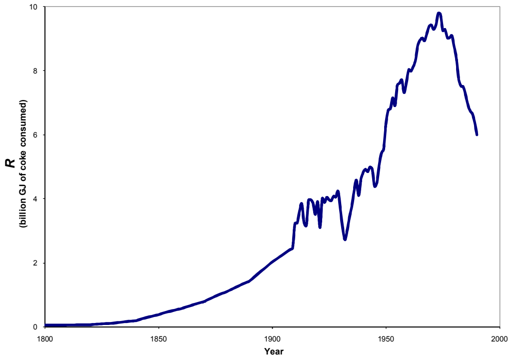


FIGURE A2: Resources Consumed (*R*) in Primary Aluminum Production (World) [b]

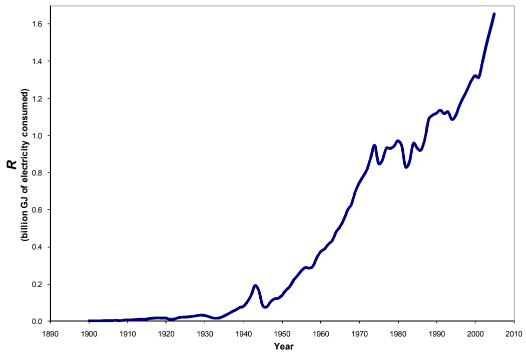


FIGURE A3: Resources Consumed (*R*) in Nitrogen Fertilizer Production (World) [c]

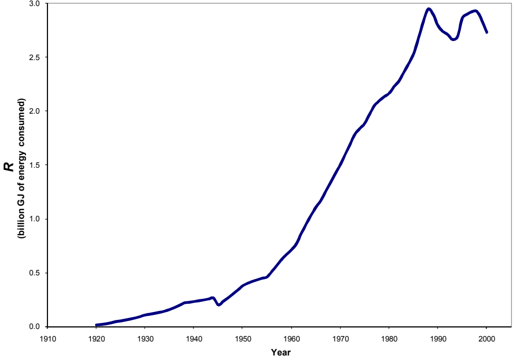


FIGURE A4: Resources Consumed (*R*) in Electricity Generation from Coal (US data) [d]

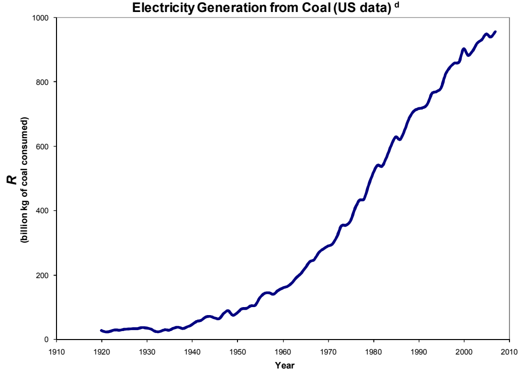


FIGURE A5: Resources Consumed (*R*) in Electricity Generation from Oil (US data) [d]

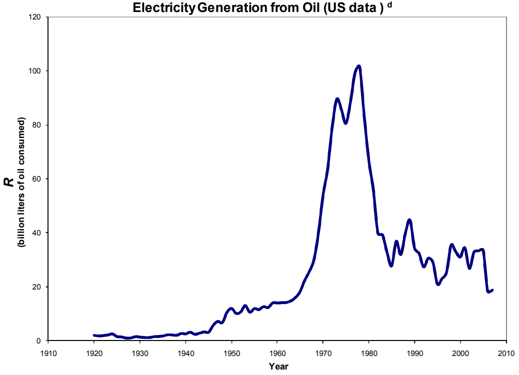


FIGURE A6: Resources Consumed (*R*) in Electricity Generation from Natural Gas (US data) [d]

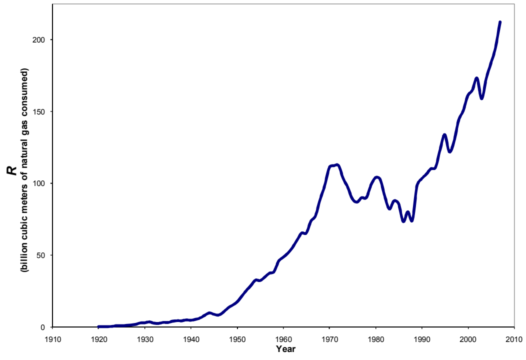


FIGURE A7: Resources Consumed (*R*) in Freight Rail Travel (US Class I railroads) [e]

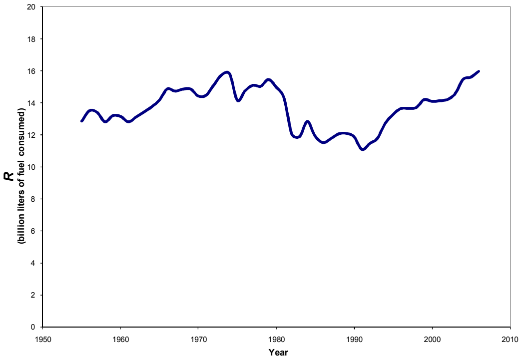


FIGURE A8: Resources Consumed (*R*) in Passenger Air Travel (US airlines) [f]

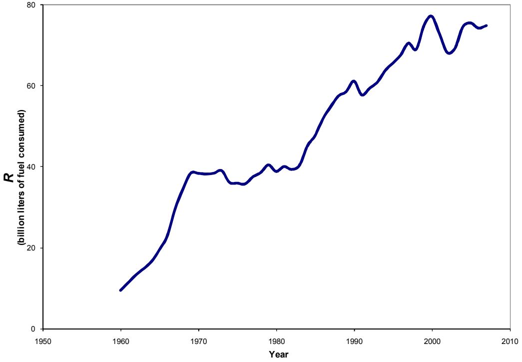


FIGURE A9: Resources Consumed (*R*) in Motor Vehicle Travel (US data) [g]

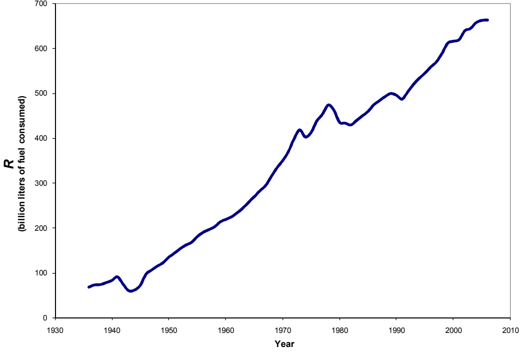


FIGURE A10: Resources Consumed (*R*) in Refrigeration [h]

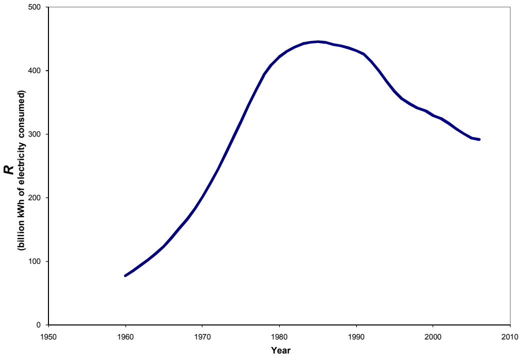


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Figure References

[a] Pig iron production

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[b] Aluminum production

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[c] Nitrogen fertilizer production

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[d] Electricity generation

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[e] Freight rail travel

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[f] Passenger air travel

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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 USA, and Japan. Given that these countries were generally quite technologically advanced at the time data was collected, the efficiency data shown represent some of the most efficient technology available for pig iron smelting at a given time. The actual global average efficiency would be lower, given the technologies in use in less technologically-advanced countries.

3. The primary method of aluminum smelting is the Hall-Heroult process. This process, independently invented in 1886 by Charles Hall in the US and Paul Heroult in France, is the process by which aluminum oxide, produced from bauxite, is reduced, producing aluminum.

4. The Haber-Bosch process, invented by Fritz Haber and commercialized by Carl Bosch in the early 1900s, is the process by which ammonia is synthesized from nitrogen and hydrogen. The Haber-Bosch process is the primary method of nitrogen fertilizer production. The efficiency data used in the nitrogen fertilizer analysis represent the most efficient technology available at a given time. Thus, the actual global average efficiency would be lower, given the technologies in use in less technologically-advanced plants.

   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 (Ibid.).

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 long downward trend in efficiency is attributable to various factors, including fuel substitution and power plant 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, which is primarily found in the Western US, also has lower heating values. Thus, the use of Western low-sulfur coal resulted 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 be 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. The 1970 Clean Air Act, as described above, established stricter pollution controls on power plants. However, 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, 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 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 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, which restricted the construction of power plants that used oil or natural gas, 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 that has continued to this day.

8. In the US, freight railroads are categorized using a system designated by the Surface Transportation Board. This classification system has three categories, Class I, Class II, and Class III, which are based on operating revenue. In 2006, Class I railroads had operating

revenues of $346.8 million or more, Class II railroads had operating revenues between $27.8 million and $346.7 million, and Class III railroads had operating revenues less than $27.7 million (AAR 2007). These monetary cut-offs are adjusted annually for inflation.

In 2006, there were only seven Class I railroads in the US, including railroads such as Norfolk Southern, Union Pacific, and CSX Transportation. Although limited in number, Class I railroads accounted for 67% of all US freight rail mileage and 93% of all US freight rail revenue in 2006 (Ibid.).

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. It should be noted that 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 production data, and fleet averaging, in the case of efficiency data. For annual production 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. In the cases of motor vehicle travel and refrigeration, earlier trends of declining efficiency were reversed in large part due to government efficiency mandates. While the efficiency of other activities, including electricity generation, freight rail travel, and passenger air travel, were clearly also affected by legislation, motor vehicle travel and refrigeration were unique in

that in these cases, efficiency itself was explicitly legislated. These cases, and the efficiency mandates that contributed to these cases, will be discussed later in greater detail.

15 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 such as plastics and aluminum substituted for steel, not iron. However, given the strong link between the two, a decline in steel use naturally 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).

16. 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 fact that rail companies could now close down unprofitable sections of track allowed for a reduction in operating costs, which also improved profitability.

Another factor driving the revitalization of the industry was the increase in oil prices in the 1970s, which had two important effects. The high oil prices made transport by freight rail, which is more fuel efficient per tonne-kilometer than transport by truck, more attractive, thus helping rail to gain market share (Pauly et al. 1982, Williams 1985, Railway Age 1990, Duke et al. 1992). The high oil prices also helped to increase demand for domestic coal. Railroads, which provided the most effective means of transporting coal from Western mines to US factories and utilities, thus benefited greatly (Pauly et al. 1980).

17. The deregulation of the rail industry led to many other efficiency improvements. The ability to set rates allowed rail companies to fill trains that may have previously run empty on return trips with low-rate cargo, thus improving efficiency (Flint 1986). The ability to close unprofitable rail lines allowed companies to discontinue service on less-traveled sections of track, sections that had in some cases deteriorated to the point that trains were forced to travel as slowly as 10 miles per hour (Pauly et al. 1980). 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).

18. 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).

19. 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 at al. 2001). In general, it takes about 10 to 15 years for the US aircraft fleet to reach the efficiency levels of a new aircraft (Lee at al. 2001). This lag, along with considerable time spent in development, certification, and production, means 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 (Ibid.).

    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.

20. This period of declining efficiency 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).

21. 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.

22. 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).

23. While the number of hours of refrigeration an individual refrigerator provides is generally limited by the number of hours in a year, American households have increasingly added second refrigerators, thereby increasing the total hours of refrigeration used each year by a single household. From 1993 to 2005, the percentage of US household with two or more refrigerators has steadily increased, from just under 15% in 1993 to over 22% in 2005 (US DOE 1993, US DOE 1997, US DOE 2001, US DOE 2005).

24. 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).

25 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.).

26. It is true that 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.

27. Increases in affluence leading to increases in demand, and thus increases in quantity, applies in the case of normal goods. In the case of inferior goods, for which consumption decreases as income increases, increases in affluence lead to decreases in demand, and thus decreases in quantity.

28. 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

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> 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).

29. 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).

30. 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.