Can Efficiency Improvements Reduce Resource Consumption?

A Historical Analysis of Ten Activities

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Supporting information is available on the *JIE* Web site

Summary

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

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 (Fiksel 1996; Graedel and Allenby 1998; Anastas and Zimmerman 2003; Allwood et al. 2013). 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).

Although encouraging engineers to focus on efficiency improvements certainly has economic and social benefits, the notion that such improvements lead to overall reductions in resource consumption is less certain. After all, engineers have successfully realized efficiency improvements for centuries; yet, despite these product- and process-level efficiency improvements, absolute system-level reductions in resource consumption have not generally occurred. Instead, driven by growing population, increasing affluence, changing consumer behavior, and other factors, resource consumption has continued to increase. Clearly, in order for efficiency improvements to reduce

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overall resource consumption, these technological innovations must outpace increases in the quantity of goods and services provided. Already challenging, this requirement is made still more difficult by the fact that efficiency and quantity are not entirely independent and can, in fact, drive one another (Jevons 1865). This relationship creates an underlying tension between the engineer's view of efficiency improvements, in which efficiency improvements are seen as reducing resource consumption, and the economist's view of efficiency improvements, in which efficiency improvements are seen as potentially increasing resource consumption (Herring 1998, 2006; Smil 2003; Herring and Sorrell 2009).

The work presented here investigates the historical relationship between the incremental product- and process-level efficiency improvements made by engineers and the quantity of goods and services provided to society. Historical data for ten different engineering activities are presented, and specific periods in which efficiency improvements did successfully outpace increases in quantity—thus resulting in overall reductions in the consumption of energy resources—are identified and analyzed.

Background

In framing the relationship between efficiency improvements and resource consumption, the *IPAT* identity can be used. This identity disaggregates impact (I) into the product of population (P), affluence (A), and technology (T). It can be written as equation (1):

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

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). Whereas this disaggregation allows one to focus on the individual factors that contribute to humankind's impact on the earth, it is important to note that these terms are not independent (Ehrlich and Holdren 1972).

Many variants on the *IPAT* identity exist, variants that often either combine terms for added simplicity or further disaggregate terms for added resolution. In discussing the role of efficiency improvements in reducing resource consumption, the basic *IPAT* identity shown in equation (1) can be further disaggregated to equation (2):

$$\begin{aligned} Impact = Population\ x \frac{GDP}{Population} x \frac{Quantity}{GDP} \\ x \frac{Resources}{Quantity} x \frac{Impact}{Resources}, \end{aligned} \tag{2}$$

where "Quantity" refers to the quantity of goods and services provided in a society and "Resources" refers to the amount of resources consumed. It can be easily shown that other variants of the *IPAT* identity, including the Kaya Identity and the ImPACT Identity, are, in fact, contained within equation (2) (Yamaji et al. 1991; Chertow 2000; Waggoner and Ausubel 2002).

In focusing on the role of technology-based solutions in reducing resource consumption, the first few terms in equation (2) can be combined, yielding equation (3):

$$Impact = Quantity\ x \frac{Resouces}{Quantity} x \frac{Impact}{Resouces}. \tag{3}$$

In focusing on resource consumption, as compared to environmental impact, equation (3) can be further simplified to equation (4):

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

As defined above, the left side of equation (4) represents the amount of resources consumed, whereas the first term on the right-hand side represents the quantity of goods and services provided. The second term on the right-hand side of equation (4), representing the amount of resources consumed per quantity of goods and services provided, is a measure of resource intensity, the inverse of which is resource productivity (Dahlström and Ekins 2005; Huppes and Ishikawa 2005). Resource productivity, also known as resource-use efficiency, represents the quantity of goods and services provided per amount of resources consumed. Thus, equation (4) can be rewritten as equation (5):

$$Resources = Quantity\ x \frac{1}{Efficiency}, \tag{5}$$

where efficiency represents resource-use efficiency. From equation (5), it is clear that in order for efficiency improvements to successfully reduce resource consumption, the rate of improvement in 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, as shown in equation (6),

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

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

Previous Work

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

At the same time, the quantity of goods and services provided has also been tracked, often by industry groups and government agencies. U.S. government agencies ranging from the U.S. Geological Survey (USGS) to the U.S. Department of Transportation (US DOT) track various quantities, from the amount of certain materials produced to the amount of vehicle-miles traveled, respectively (US DOT 2011; USGS 2013). Smil and Ayres have also tracked the generally increasing quantities of goods and services provided, from the number of motor vehicles in the world to the amount of horsepower used on farms in the United States (Smil 1999; Ayres et al. 2003).

Whereas historical data on efficiency and quantity have been collected, it is the direct quantitative comparison of these data sets that is of particular interest in this work. Because the product of these two values is resource consumption—as shown in equation (5)—comparing the rate of improvement in efficiency with the rate of increase in quantity is critical to understanding overall trends in resource consumption. Clearly, the large-scale trends in the consumption of energy resources are well known, and the fact that overall increases in quantity are outpacing overall improvements in efficiency is not new. However, through a quantitative comparison of these rates of change, across a wide range of different activities and time periods, the dynamic interplay between technological innovation, market forces, and government policy can be explored. These analyses also reveal time periods in which improvements in efficiency did outpace increases in quantity, contributing insights into how future efficiency improvements may be leveraged to realize reductions in resource consumption.

The overall approach taken here, which isolates and analyzes the critical factors driving a particular output—namely, efficiency and quantity driving resource consumption—bears similarities to decomposition analysis. Works by Waggoner, Wernick, and Ausubel utilize similar decomposition approaches to disaggregate the critical factors contributing to various metrics, including environmental impact and consumption (Waggoner et al. 1996; Wernick et al. 1997). Decomposition approaches have also been used to identify the critical determinants of changes in quantity—including consumer preference, the material composition of products, and GDP—and evaluate the importance of each (Roberts 1988). Other decomposition analyses have helped to address the material intensity of use and its relation to economic output (Considine 1991; Cleveland and Ruth 1998). In general, decomposition provides a link between broader aggregate economic or environmental effects and a collection of specific factors that contribute to those effects. These techniques are part of a larger field of decomposition analysis that includes index decomposition analysis, which relies on sector- 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 equation (5), and the relative contributions that each of these two factors makes to resource consumption, are analyzed.

More recent discussions of resource consumption increasingly focus on the idea of material and resource efficiency. Though definitions vary, these approaches generally focus on the efficient use of goods and materials, with strategies ranging from dematerialization to material substitution to extending product lifetimes (WRAP 2011; Allwood et al. 2013). Resource efficiency also focuses on the decoupling of economic performance from resource use, thus allowing the rate of economic growth to outpace the rate of resource consumption (UNEP 2011; SCU 2012). This concept of resource efficiency is, in many ways, analogous to that of resource-use efficiency, as described earlier and included in equation (5). The analyses presented here take a historical look at aspects of resource efficiency across ten activities.

Historical Trends in Efficiency and Quantity

Historical efficiency and quantity data were compiled to examine whether 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, equation (6) would have been satisfied, and reductions in resource consumption would have occurred. The data presented here cover ten activities: pig iron production; aluminum production; nitrogen fertilizer production; electricity generation from coal; electricity generation from oil; electricity generation from natural gas; freight rail travel; passenger air travel; motor vehicle travel; and residential refrigeration. For each of the activities analyzed, quantity is measured as the quantity of goods or services provided, whereas efficiency is measured as the quantity of goods or services provided per amount of resources consumed. In each case, the resources consumed are energy-related resources, from liters of fuel to megajoules (MJ) of electricity.

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

For each of the ten activities analyzed, the geographic and temporal boundaries of the analyses were quite varied, as summarized in table 1. Geographic boundaries were drawn to either include the entire world or only the United States. For goods and services for which an integrated global market exists, as is the case with pig iron, aluminum, and nitrogen fertilizer, global

Table 1 Historical trends in efficiency and quantity

Activity	*Time period*	*Geographic region*	*Unit of efficiency (e)*	*Unit of quantity (Q)*	*Average annual $\Delta e/e$ (%)*	*Average annual $\Delta Q/Q$ (%)*	*Average $\Delta Q/Q$/ average $\Delta e/e$*
Pig iron	1805–1990	World	kg of pig iron per GJ of coke	kg of pig iron	1.4	4.1	3.0
Aluminum	1905–2005	World	kg of aluminum per GJ of electricity	kg of aluminum	1.2	9.8	8.3
Nitrogen fertilizer	1925–2000	World	kg of nitrogen per GJ of energy	kg of nitrogen	1.8	7.5	4.2
Electricity from coal	1925–2009	United States	MJ of electricity per kg of coal	MJ of electricity	0.9	5.2	5.9
Electricity from oil	1925–2009	United States	MJ of electricity per liter of oil	MJ of electricity	1.1	5.1	4.5
Electricity from natural gas	1925–2009	United States	MJ of electricity per cubic meter of natural gas	MJ of electricity	1.5	8.3	5.6
Freight rail travel	1955–2009	United States	Revenue tonne-km of freight rail travel per liter of fuel	Revenue tonne-km of freight rail travel	1.9	2.0	1.1
Passenger air travel	1955–2009	United States	Available seat-km of passenger air travel per liter of fuel	Available seat-km of passenger air travel	1.1	6.5	6.2
Motor vehicle travel	1940–2009	United States	Vehicle-km of motor vehicle travel per liter of fuel	Vehicle-km of motor vehicle travel	0.4	3.6	10.0
Residential refrigeration	1960–2009	United States	Hour-cubic meters of residential refrigeration per MJ of electricity	Hour-cubic meters of residential refrigeration	1.4	3.9	2.9

Note: In these activities, increases in quantity outpace improvements in efficiency by factors ranging from 1.1 to 10.0.
kg = kilograms; GJ = gigajoules; MJ = megajoules; km = kilometers.

data were used. Using global data for these activities prevents geographic shifts in production from affecting the analyses. For goods and services for which an integrated global market does not exist, as is the case with electricity generation, vehicle travel, and residential refrigeration, U.S. data were used. For these activities, which tend to be services, changes in the quantity provided generally represent changes in demand, as opposed to any geographic shifts in production.

Temporal boundaries were determined based on the life cycle of a technology as well as on data availability. Whereas many of the activities analyzed have undergone radical technological transformations—refrigeration, for example, has transitioned from ice houses to electric refrigerators—only the most recent technology, in this example, electric refrigerators, is examined.[1] Such limits help to ensure that the goods or services for a given activity remain roughly comparable over the time periods analyzed. However, even with these limits in place, there can still be changes across a range of performance measures, including efficiency, convenience, and safety, among others. Though these changes in quality could be captured using multiattribute utility analysis or hedonic regression modeling, such analyses involve significantly more information, including objective data about performance characteristics as well as subjective data about the value of these performance characteristics. Such analyses are outside the scope of this work. However, by selecting temporal boundaries to ensure a generally comparable set of goods and services, the effects of changing utility can be minimized. For activities analyzed here that have experienced increases in utility, this performance improvement has likely helped to spur further increases in quantity.

Setting temporal boundaries around a single technology also restricts the types of efficiency improvements considered. In particular, whereas incremental improvements in a given technology are included, radical technological transformations, including the substitution of new technologies, are not. Excluding such changes can lead to lower calculated rates of efficiency improvement. However, such a simplification does avoid the significant informational requirements, as described above, needed to capture changes in the quality of a good or service. Also, the incremental efficiency improvements that are

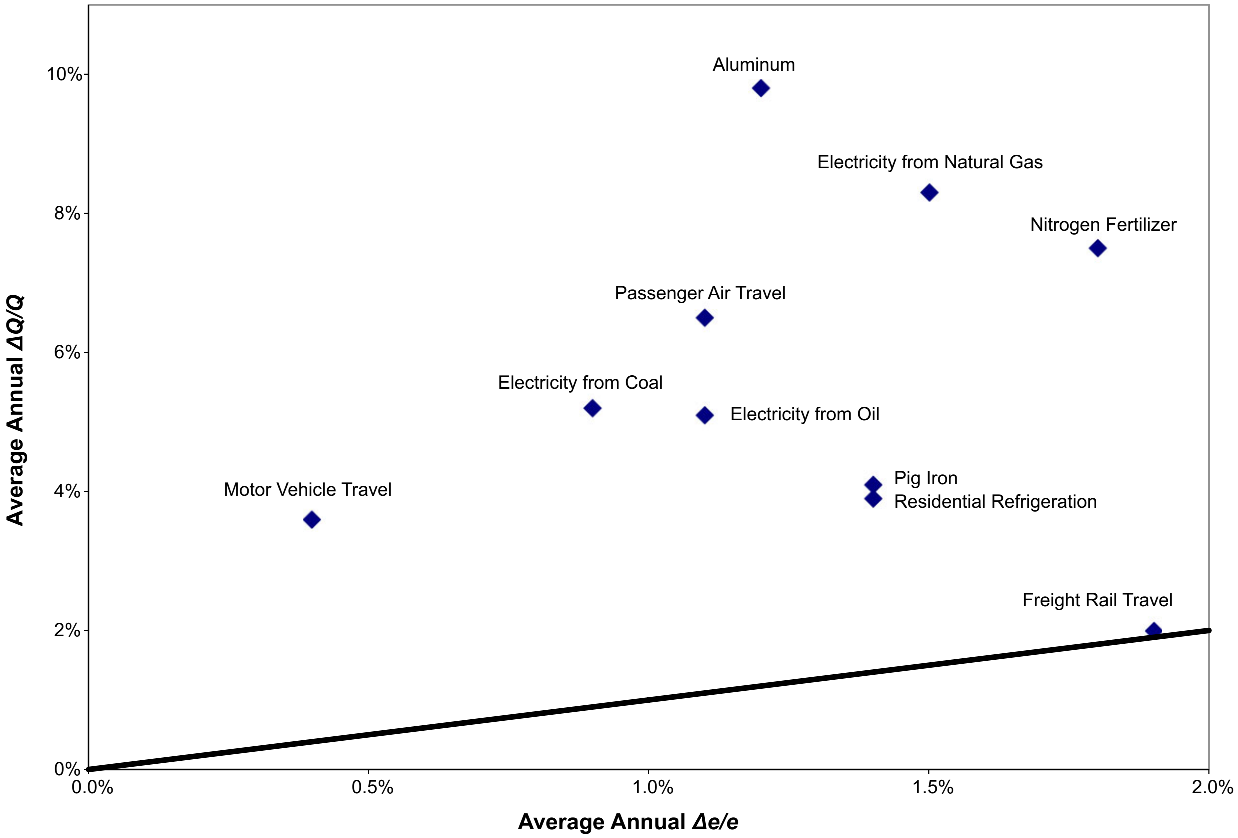

Figure 1 Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for ten activities. The time periods covered vary by activity and can be found in table 1. The solid diagonal line is the line of constant resource consumption, representing the condition in which the average annual $\Delta e/e$ is equal to the average annual $\Delta Q/Q$.

captured in this analysis do represent the more common type of efficiency improvement.

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

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. Positive values for changes in efficiency indicate efficiency improvements, whereas 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, equation (6) was not satisfied. Thus, despite significant improvements in efficiency, the resources consumed by each of these activities, as calculated using equation (5), has increased. Additional detailed information on the underlying efficiency and quantity data for these ten activities, including analyses, plots, and references, are provided in the Supporting Information on the Journal's website.

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 1. The solid diagonal line in figure 1 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

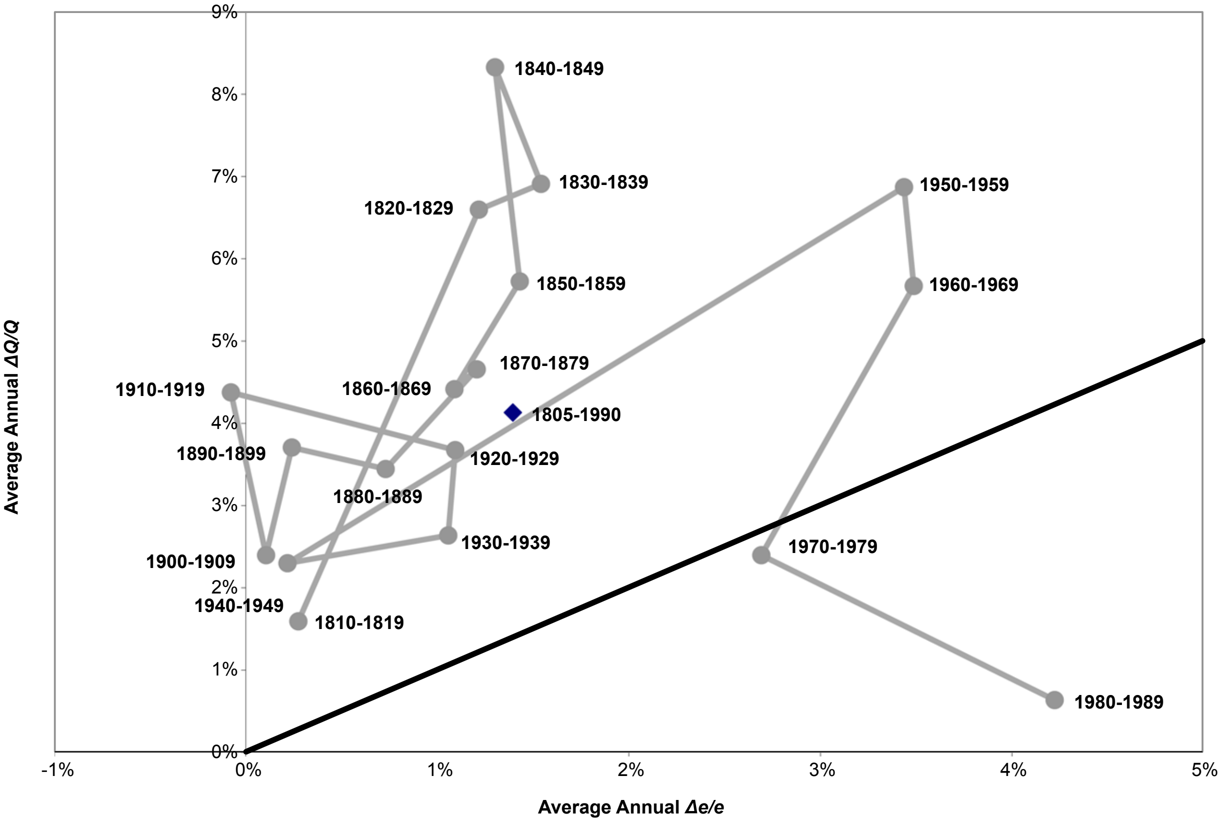

Figure 2 Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for worldwide pig iron production over 18 decades.

equation (6) is not satisfied, whereas points below this line represent periods of decreasing resource consumption, where equation (6) is satisfied. From figure 1, it is clear that in each of the ten cases examined above, equation (6) is not satisfied.

Decade-by-Decade Analysis

Whereas the long time periods analyzed above raise questions about the ability of incremental efficiency improvements to reduce resource consumption, a decade-by-decade analysis of these activities reveals a few time periods in which improvements in efficiency did outpace increases in the quantity of goods and services provided, resulting in periods of decreasing resource consumption. One such example occurs in the case of pig iron. Figure 2 plots the average annual change in efficiency, $\Delta e/e$, versus the average annual change in quantity, $\Delta Q/Q$, for world-wide pig iron production, both overall and on a decade-by-decade basis. As in figure 1, the dark diagonal line in figure 2 represents a line of constant resource consumption; points above this line represent periods of increasing resource consumption, whereas points below this line represent periods of decreasing resource consumption.

As can be seen in figure 2, world-wide pig iron production did experience two decades, 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 1.5%, 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 unprecedented in the long history of pig iron production. Though more recent efficiency data are 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 likely continued to today.

This period from 1970 to 1989 proved to be a turbulent time for the iron and steel industry, marked by slowing worldwide economic growth and the beginning of a geographic shift in production, away from industrialized nations and toward developing countries (Roberts 1988; Hudson and Sadler 1989; Warren 2001; Fenton 2005). A variety of factors, including rising pig iron prices, the greater availability of substitute materials such as plastics and aluminum, and a slowdown in infrastructure building in developed countries, accounted for the slower average annual increases in pig iron quantity during this period (Hudson and Sadler 1989; Mangum et al. 1996; Warren 2001; Tilton 2002).[2] This period was also marked by rising energy and raw material costs, which pressured pig iron producers to become more efficient. Improvements such as the use of pelletized ore, increases in hot blast temperatures, and increases in blast furnace size all contributed to rapidly improving

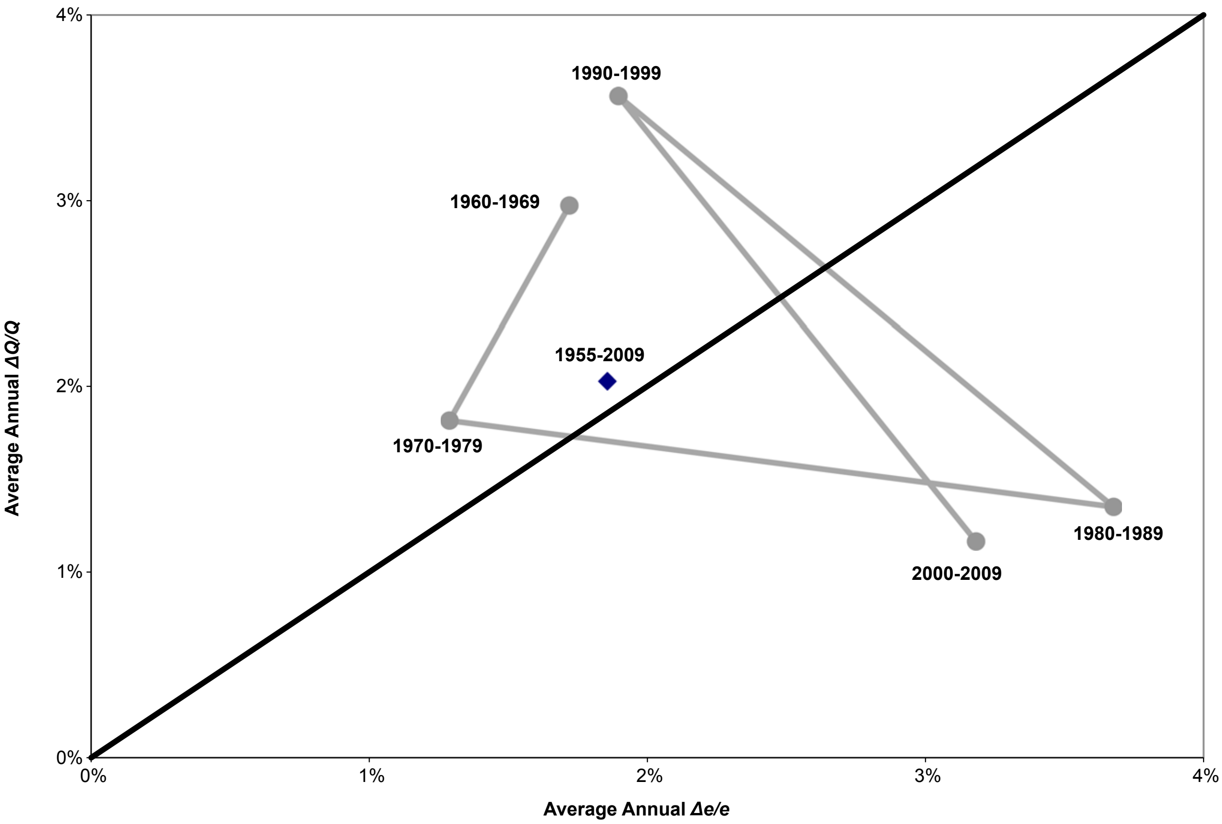

Figure 3 Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for U.S. freight rail travel over five decades.

efficiencies (Ruth 1995; de Beer et al. 1998; Smil 1999; Fenton 2005).

Another activity in which, on a decade-by-decade basis, improvements in efficiency outpaced increases in quantity is freight rail travel. The data for freight rail travel by U.S. Class I railroads, over five decades from 1955 to 2009, is shown in figure 3. The dark diagonal line in figure 3 represents a line of constant resource consumption.

As can be seen in figure 3, U.S. freight rail travel did experience two decades in which improvements in the fuel efficiency of freight rail travel outpaced increases in the quantity of freight rail travel provided. Both the 1980s and the 2000s featured historically high rates of efficiency improvements and historically low rates of quantity growth.

In general, the 1980s marked a renaissance in U.S. freight rail travel, and 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 shut down unprofitable rail lines, helped the rail industry to both increase revenue and reduce costs (Duke et al. 1992; Braeutigam 1993). These actions also had important effects on fuel efficiency, because fewer lines, now carrying more freight, proved to be more efficient (Business Week 1984; Flint 1986).[3] 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, as well as 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; Williams 1985; Flint 1986).[4]

In the 2000s, increasing fuel prices drove considerable improvements in efficiency. With fuel, at times, accounting for as much as one quarter of operating expenses, improving efficiency represented an important means to cut costs. In terms of quantity, the latter part of the 2000s featured a slowing of quantity growth, including, in 2009, the largest percentage decrease in quantity since 1949 (Association of American Railroads [AAR] 2010). This decrease was driven by the recession of the late 2000s, as well as by a drastic decline in the amount of coal transported, as coal for electricity generation faced stiff competition due to falling natural gas prices. With coal representing over 45% of freight rail tonnage, this decline in coal transport had a profound effect on overall quantity.

Another transportation activity, passenger air travel, also showed a single, decade-long period in which improvements in efficiency outpaced increases in quantity. Figure 4 plots average annual changes in efficiency and average annual changes in quantity on a decade-by-decade basis for passenger air travel. The dark diagonal line again represents a line of constant resource consumption.

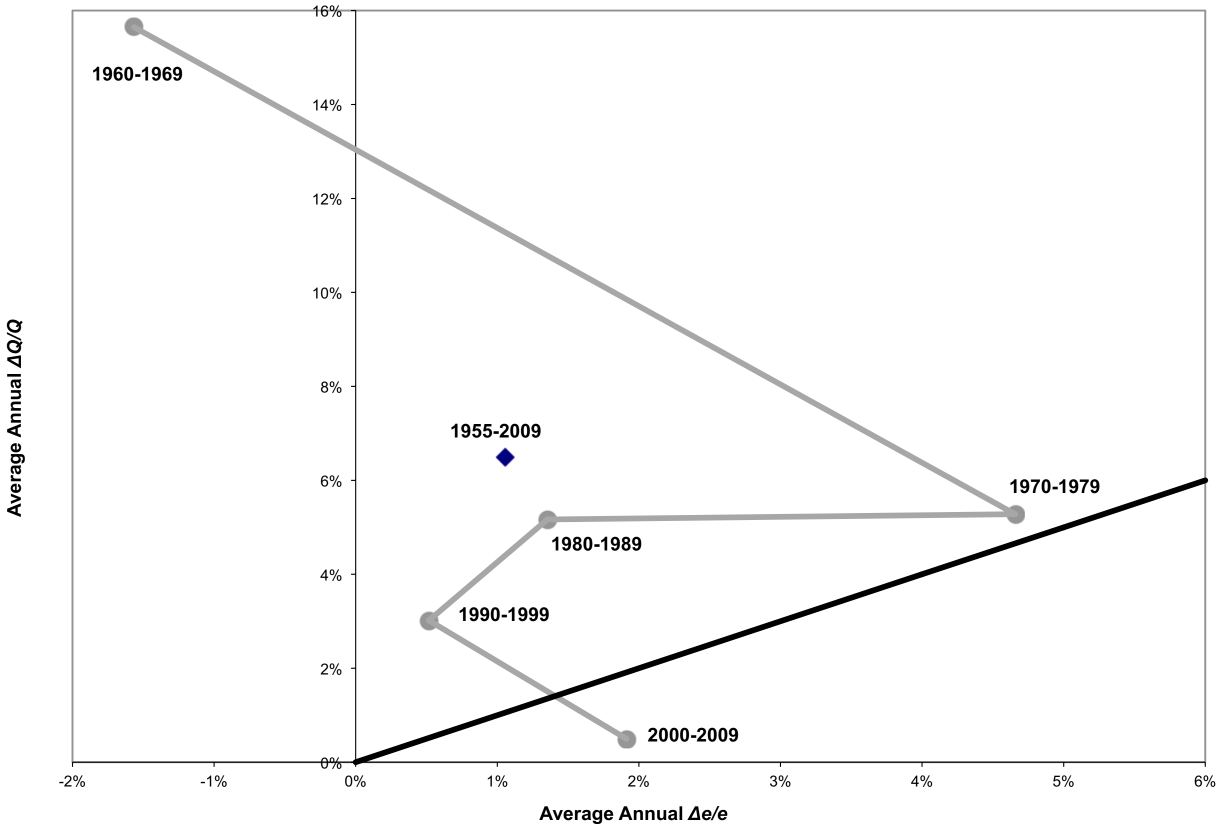

Figure 4 Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for U.S. passenger air travel over five decades.

From 2000 to 2009, the average annual change in efficiency exceeded the average annual change in quantity for U.S. passenger air travel. This period was marked by an increased rate of efficiency improvement and a historically low rate of quantity increase. The low average annual growth in quantity was the result of two shorter periods of declining passenger air travel during this decade. The first of these periods was driven by the economic slowdown of the early 2000s, the events of September 11, 2001, and the outbreak of severe acute respiratory syndrome (SARS) in Asia. The second period of declining passenger air travel was driven by the recession of the late 2000s, rising operating costs for airlines, rising air travel costs for consumers, and ongoing financial instability in the industry as a whole. This decrease in average annual quantity growth from 2000 to 2009 followed a four-decade-long trend of declining growth rates. 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 shown in Figure S1-8b in the supporting information available on the Journal's website. 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; Wilen 2008).[5]

The other period in which U.S. passenger air travel nearly satisfied equation (6) was from 1970 to 1979. As compared to the 1960s, the 1970s were marked by a significantly slower rate of quantity growth and a significantly higher rate of efficiency improvement. This increase in the rate of efficiency improvement was again driven, in large part, by increasing jet fuel prices (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; from 1970 to 2009, average annual efficiency improvements increased during periods of increasing real jet fuel prices and decreased during periods of decreasing real jet fuel prices.

Although the third transportation activity examined here, U.S. motor vehicle travel, never experiences a decade in which average annual improvements in efficiency outpaced average annual increases in quantity, the dynamics of this activity over time are interesting to examine in greater depth. Figure 5 shows a decade-by-decade breakdown of average annual changes in efficiency and average annual changes in quantity for U.S. motor vehicle travel. Motor vehicle travel has made strong movements toward the line of constant resource consumption, yet has never realized a period in which equation (6) was satisfied.

Over the seven decades shown in figure 5, the average annual change in efficiency for U.S. motor vehicle travel has varied considerably. From the 1940s through the 1960s, efficiency declined as motor vehicles became larger and more powerful (Hirsh 1999). In the 1970s and early 1980s, consumer concerns about gasoline availability, higher gasoline

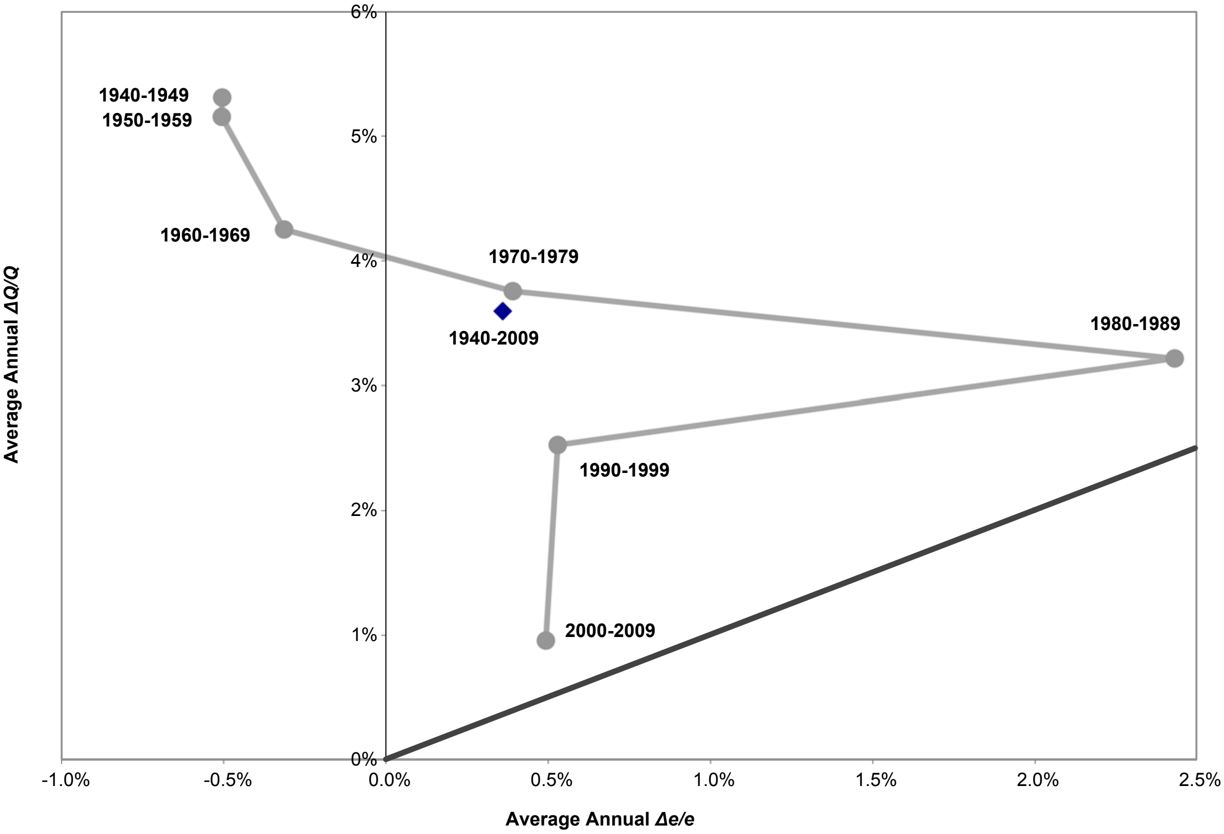

Figure 5 Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for U.S. motor vehicle travel over seven decades.

prices, and government legislation in the form of corporate average fuel economy (CAFE) standards led to an extended period of improving efficiency. Figure S1-9b in the supporting information available on the Journal's website 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 5. However, in the 1990s and 2000s, consumer demand for larger, 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 U.S. 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 traveled has decreased in each decade; if this trend continues, stabilizing or reducing resource consumption in U.S. motor vehicle travel could become easier.

One activity in which improvements in efficiency did outpace increases in quantity on a decade-by-decade basis is residential refrigeration in the United States. Figure 6 plots the average annual change in efficiency, $\Delta e/e$, and the average annual change in quantity, $\Delta Q/Q$, for U.S. residential refrigeration, both overall and on a decade-by-decade basis.

Figure 6 indicates that residential refrigeration in the United States succeeded in crossing below the line of constant resource consumption. The efficiency trends show that before the 1980s, refrigerator efficiency decreased, with refrigerators increasing in size and adding additional features (Rosenfeld 1999). However, after this period, efficiency improved considerably, driven primarily by a series of state and federal efficiency mandates on appliances.[6] At the same time, the quantity of residential refrigeration continued to increase, as the size of refrigerators, the number of American households, and the number of refrigerators used per household have all increased.[7]

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

Discussion

In examining the activities presented here, it is important to identify and understand the circumstances under which efficiency improvements were able to outpace increases in quantity. If such conditions can be emulated, there exists the possibility

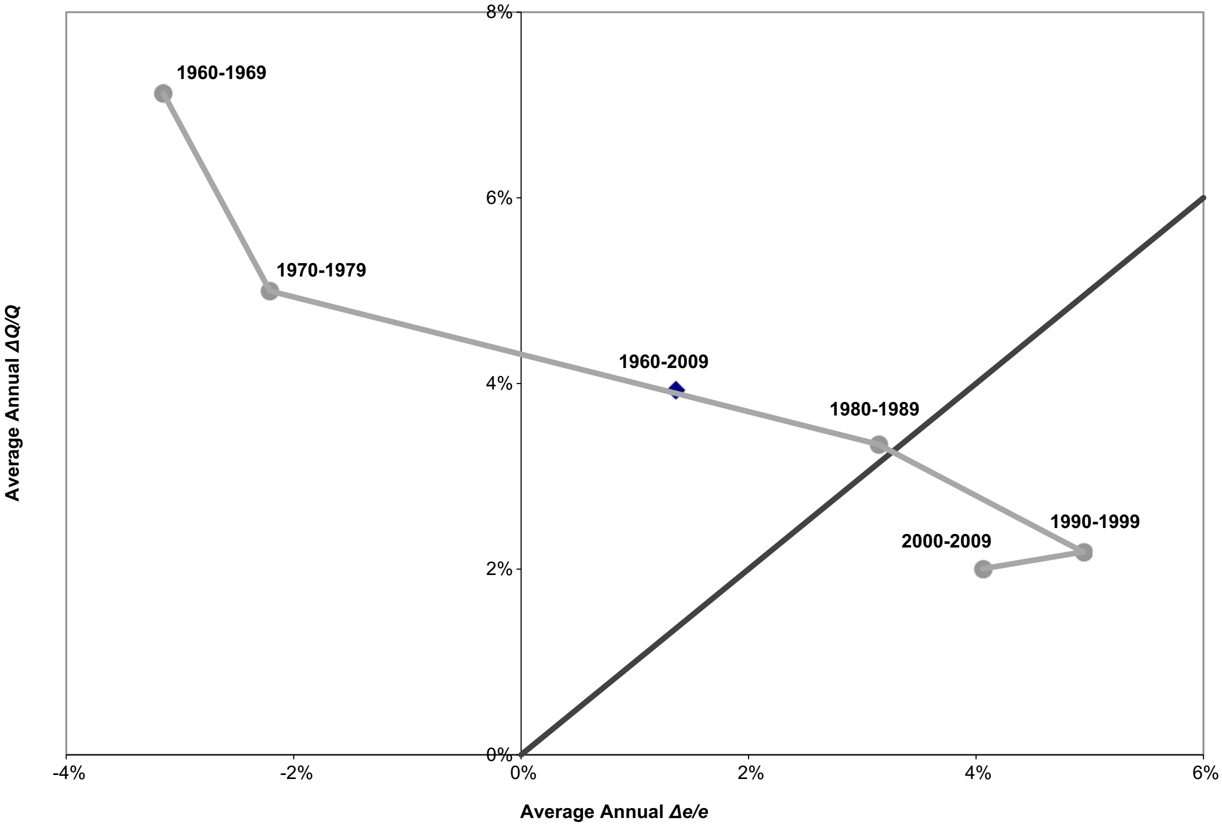

Figure 6 Average annual $\Delta Q/Q$ versus average annual $\Delta e/e$ for U.S. residential refrigeration over five decades.

that future efficiency improvements may also lead to reductions in the consumption of energy resources.

In each of the periods of reduced resource consumption presented here, different circumstances drove each case. For worldwide pig iron production, U.S. freight rail travel, and U.S. passenger air travel, the periods of reduced resource consumption corresponded with turbulent times in their respective industries. In the case of worldwide pig iron production and U.S. passenger air travel, volatile fuel prices and a weak global economy led to this instability; in the case of U.S. freight rail travel, deregulation and rapidly changing demand led to industry upheaval. For U.S. residential refrigeration, a series of increasingly stricter efficiency mandates led to a prolonged period of reduced resource consumption in the 1990s and 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, U.S. motor vehicle travel can also be included. In the case of U.S. motor vehicle travel, both fuel prices and efficiency mandates contributed to a period of stabilized resource consumption. In light of this example, as well as the effect of fuel prices on U.S. passenger air travel, price pressures may also represent a reproducible approach for future reductions in resource consumption.

Efficiency Mandates

As noted in the case of U.S. residential refrigeration, efficiency mandates can be used to reduce resource consumption. However, the impact of the rebound effect—the effect by which improvements in efficiency can lead to increases in the quantity of goods and services provided and consumed—can be critical to success. With little or no rebound, efficiency mandates can lead to a case in which equation (6) is satisfied (Lovins 1988; Grubb 1990, 1992). 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 (Khazzoom 1980, 1982, 1987, 1989; Brookes 1990, 1992).

Whereas many appliances exhibit little direct rebound, the case of U.S. residential refrigeration appears to be a bit different (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). Though the number of hours a single refrigerator can be used is typically fixed, increasingly larger refrigerators have led to increased utlitization. In fact, the average capacity of a new refrigerator has increased over 50% during the time period analyzed here (Rosenfeld 2003). Increasing ownership has also occurred, with almost 23% of U.S. households in 2009 owning two or more refrigerators US DOE 2009). However, despite this rebound, the efficiency mandates for refrigerators were still sufficient to decrease the overall resource consumption of this activity. Whereas the gains in utilization and ownership may have lessened the overall reduction in resource consumption, the efficiency mandates were largely effective.

Efficiency mandates for goods and services with limited rebound may prove to be the most effective. For example, efficiency mandates on other appliances, including dishwashers and laundry machines, may also lead to reductions in resource consumption. In the case of U.S. motor vehicle travel, estimates of the rebound effect, expressed as the percentage increase in consumption resulting from a 100% improvement in efficiency, range from a few percent up to 30%, depending on the specific conditions (Greening et al. 2000; Small and Van Dender 2007; Sorrell 2007; Gillingham et al. 2013). This relatively low rebound effect may indicate another case in which efficiency mandates can lead to the reduced consumption of energy resources. Though the existence of rebound effects may erode some of the overall reduction in resource consumption, as observed in the case of residential refrigeration, efficiency mandates on motor vehicles may still prove to be useful. Indeed, past efficiency mandates on motor vehicles in the United States do appear to have played some role in helping to move motor vehicle travel closer to the line of constant resource consumption in the 1970s and 1980s, as shown in figure 5.

Price Pressures

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

Increases in prices could reduce resource consumption for other goods and services. For example, in the case of U.S. motor vehicle travel, increases in the price of motor fuel could lead to a small drop in demand in the short term and efficiency improvements in the long term (Pindyck and Rubinfeld 2001; Krueger 2005). Recent market trends provided an interesting case study, with the real price of motor fuel in the United States more than doubling from 2002 to 2008 (US DOE 2012). During the first five years of this period, the quantity of vehicle-kilometers traveled increased, and only a slow shift toward more fuel-efficient motor vehicles was observed (Krauss et al. 2007; US DOT 2011). However, during the last few years of this period of rising fuel prices, U.S. consumers increasingly shifted to smaller, lighter, and more fuel-efficient vehicles while, at the same time, reducing the quantity of vehicle-kilometers traveled (Vlasic 2008; Porter 2012). In fact, vehicle-kilometers traveled decreased in 2008, and again in 2009, the first year-on-year decreases since 1980 (US DOT 2011). Although other factors besides rising motor fuel prices—including the recession of the late 2000s—likely affected trends in the efficiency and quantity of U.S. motor vehicle travel during this period, if these trends were to continue, an overall reduction in resource consumption could be realized.

Whereas the price pressures in the cases of U.S. airline passenger travel and U.S. motor vehicle travel came about through market forces, other price pressures could be legislated, if appropriate, perhaps through revised tax policies. Such an approach is by no means straightforward, but may prove to be an effective approach to reducing resource consumption (Portney et al. 2003; Porter 2012). In such a scenario, the size of the price increase does play an important role, both in terms of political feasibility and in terms of effect. For cases in which considerable price increases may be necessary, efficiency mandates may prove to be the more politically feasible approach (Hughes et al. 2006).

Conclusion

Historically, efficiency improvements have generally not proven to be successful in reducing humankind's overall consumption of energy resources. Of the 80 decades examined across ten activities, only a handful of decades had rates of efficiency improvement that matched or exceeded rates of quantity increase. In these cases, efficiency mandates, price pressures, and industry upheaval contributed to these periods of stabilized or decreased resource consumption. Based upon these historical cases, it does appear that efficiency mandates and price pressures, under appropriate circumstances, may prove effective in reducing resource consumption. However, incremental 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 incremental 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 are 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 incremental product- and process-level efficiency improvements play out in the larger system. Whereas efficiency improvements are worthwhile from an economic and social perspective, in the absence of appropriate external incentives, such efficiency improvements may not result in overall reductions in resource consumption.

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Notes

1. In this example, and throughout the article, refrigeration refers to the common electrical compressor refrigerator.
2. The majority of pig iron produced in the world is used to make steel. In many applications, competing materials—including plastics and aluminum—substituted for steel, not iron. However, given the strong link between the two, a decline in steel use led to a decline in pig iron use.
3. Giving rail companies the ability to set their own rates made the rail industry much more competitive with trucking, because 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).

   The ability to close unprofitable rail lines allowed companies to discontinue service on less-traveled sections of track, thus reducing operating costs and improving profitability. The closing of rail lines, along with a recession-related equipment surplus in the early 1980s, also improved efficiency, by allowing older, less-efficient equipment to be removed from service (AAR 1983).
4. The new innovations in rail cars included "piggyback" or "trailer on flat car" 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, computer-controlled locomotives, and the use of advanced wheel slip-control systems, also improved fuel efficiency, although such improvements generally took some time to manifest themselves at the fleet level (Shedd 1984).
5. Whereas both technological and operational 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 development, certification, and production times can cause a considerable lag in technology (IPCC 1999; Lee et al. 2001). Some have estimated this time delay between initial development and actual impact at the fleet level to be as much as 25 years (Lee et al. 2001).

   Operational changes, however, can yield more immediate results. Improvements in air traffic management, including reducing air and ground delays, improving flight routing, and reducing vertical separation minimums, can lead to considerable increases in fuel efficiency (IPCC 1999; Lee et al. 2001; McCartney 2006; Heimlich 2007). Other common operational approaches 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).
6. In the United States, starting in the 1970s, states began mandating minimum efficiency requirements on new household appliances (Gellar 1995). 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).
7. From 1993 to 2009, the percentage of U.S. households with two or more refrigerators increased from just under 15% in 1993 to almost 23% in 2009 (US DOE 1993; US DOE 2009).

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Supporting Information

Additional supporting information may be found in the online version of the article at the publisher's website:

Supporting Information S1: This supporting information provides figures displaying plots of quantity and efficiency versus time, summary data, and references for data sources for each of the ten activities analyzed in the main text.

Supporting Information S2-S11: These supporting information documents provide efficiency and quantity data on the following:

S2: Worldwide pig iron production from 1805 to 1990.

S3: Worldwide aluminum production from 1905 to 2005.

S4: Worldwide nitrogen fertilizer production from 1925 to 2000.

S5: US electricity generation from coal from 1925 to 2009.

S6: US electricity generation from oil from 1925 to 2009.

S7: US electricity generation from natural gas from 1925 to 2009.

S8: US freight rail travel from 1955 to 2009.

S9: US passenger air travel from 1955 to 2009.

S10: US motor vehicle travel from 1940 to 2009.

S11: US residential refrigeration from 1960 to 2009.