Efficiency and Production:

Historical Trends for Seven Industrial Sectors

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Abstract

A review of historical data for resource efficiency, production, and total resource usage for seven industrial sectors reveals several clear patterns of activity. For example, over their approximately 50 to 200 year histories the manufacturing, utilities and service sectors reviewed here, all showed significant average increases in all three measures. However, on average, production increases outpaced efficiency increases by substantial margins leading to average increases in total resource usage. For example, while the energy efficiency of pig iron production has improved by an average of over 1% annually for the last 185 years, worldwide production of pig iron over this same period of time has increased by an average of 4% annually. Aluminum production, nitrogen fertilizer production, electricity production from coal, oil, and gas, and air travel all exhibit similar trends. The correlation between efficiency and production, as well as the possible causal relationship between the two, casts serious doubts on the ability of "naturally occurring" efficiency improvements alone to reduce resource consumption and associated environmental impacts. However, efficiency and consumption data from the use phase of automobiles and refrigerators, cases in which efficiency improvements were imposed by the government, show very different trends. For example, in the case of refrigerators, government-mandated efficiency requirements, that were constantly upgraded, reversed previous trends and led to an overall reduction in resource use and impact. A similar reversal was found for automobiles, but policy inaction has allowed the original pattern of increased resource usage to reemerge. The implications of using efficiency improvements to curb total resource usage are discussed.

Introduction

In attempting to move towards a more sustainable society, efficiency is often seen as a promising solution. Industrial ecologists, business leaders, engineers, politicians, and others have all embraced efficiency as a means of preserving economic growth while reducing the amount of resources used by the economy. Indeed, efficiency improvements are often seen as "win-wins", as they allow for economic and societal gains to continue unimpeded while at the same time reducing resource consumption (DeSimone and Popoff 1997, OECD 1998, WBCSD 2000).

Technical efficiency improvements are by no means new; "naturally occurring" or "autonomous" efficiency improvements have been taking place for centuries[a]. In production activities, process efficiencies are continually being improved, thus allowing more useable output to be produced per unit of input. However, in many cases, while efficiency has improved, production has at the same time also increased, resulting in a situation in which the overall inputs to production have increased, not decreased. In addition to bringing the win-win scenario into debate, these trends have also raised questions regarding the possible causality of these trends.

This paper will explore the historical relationship between efficiency and production for seven industrial sectors, ranging from the worldwide production of pig iron to the U.S. consumption of residential refrigeration.[b] To better frame this relationship in the context of sustainability discussions, a variant of the well-known IPAT equation will be used.[c] This variant is the IPT form of the equation, where impact (I) is a product of production (P) and technology (T). Expressing technology as the reciprocal of efficiency (e) yields

$$I = P \times \frac{1}{e} \tag{1}$$

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[a] Note that during the period reviewed here, on average, fuel prices have been falling. Efficiency improvements during these periods generally accompany technology innovations and are called "autonomous" in the economics literature. We use "naturally occurring" as synonymous with "autonomous".

[b] In the case of supply-side activities such as manufacturing, the relationship between efficiency and production is of interest. In the case of demand-side activities such as product use, the relationship between efficiency and consumption is of interest.

[c] The IPAT equation is a mathematical identity that equates impact (I) to the product of population (P), affluence (A), and technology (T). A recent discussion and historical review of the IPAT equation is provided by Chertow (2000).

From (1), it is clear that in order to reduce impact, one of four different scenarios must occur: 1) production decreases with no change to efficiency, 2) efficiency increases with no change to production, 3) production decreases while efficiency increases, or 4) efficiency increases faster than production increases. The first three methods of impact reduction all require either a decrease in production or a leveling of production, and are thus not generally considered desirable by many. The fourth method of impact reduction, in which the rate of improvement in efficiency exceeds the rate of growth in production, requires the following condition:

$$\frac{\Delta e}{e} \geq \frac{\Delta P}{P} \tag{2}$$

Production and Efficiency

Production and resource efficiency data were obtained for five of the seven industrial sectors studied: three global sectors, namely pig iron production (energy and coke efficiency), aluminum production (energy efficiency), and nitrogen fertilizer production (energy efficiency), and two U.S. sectors, namely electricity generation (coal, oil and gas efficiency), and airplane travel (energy efficiency). Figures 1 through 4 show worldwide efficiency and production data for pig iron, aluminum, and nitrogen fertilizer. Process efficiencies shown in the figures are measured in terms of kilograms of product produced per unit of resource used. Resources are measured in joules of energy used, as in Figures 1, 3, and 4, or in kilograms of coal equivalent used, as in Figure 2. Production data is simply measured in kilograms of output. The data plotted in Figures 1 through 4 show almost continuous increases in both efficiency and production, suggesting a strong positive correlation between the two.[d]

Figures 5, 6, and 7 show efficiency and production data for electricity generation activities in the U.S. In these examples, significant disturbances in both efficiency and production are apparent. In the case of electricity generation from coal, shown in

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[d] Efficiency improvements often follow a logistics curve or S-curve, which plateaus over time due to thermodynamic and/or practical limits. In this flat, mature region of the logistics curve, further efficiency improvements are often realized by switching to a new technology, which corresponds to jumping to a new logistics curve (Grubler 1998, Smil 1999)

Figure 5, 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, ranging from steam turbine efficiencies[e] to fuel substitution[f]. Figures 6 and 7 show efficiency and production data for electricity generation from oil and natural gas, respectively. While efficiency data shows relatively steady improvement over time, production data shows large fluctuations. These variations are due primarily to a combination of price and supply volatility for oil[g] and natural gas[h], as well as various policy interventions. Outside of the 1970s and 80s, during which these large variations occurred, efficiency and production values in Figures 6 and 7 appear to be positively correlated.

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[e] One explanation for this declining efficiency was the fact that steam turbines at that time were beginning to approach the limits of thermal efficiency. Industry was also focusing on other performance issues in addition to efficiency, including reliability (Smil 1999).

[f] Another explanation for this decline in efficiency was the increased use of low-sulfur bituminous coal at that time. In the U.S. in the late 1960's and early 1970's, environmental concerns began to rise in prominence. As part of this increased focus on the environment, legislation was enacted, including the 1970 Clean Air Act, which established controls on certain emissions from power plants, including sulfur dioxide, nitrogen oxides, and particulates. 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. This low-sulfur coal, which also has lower heating values, was primarily found in the Western U.S. With the deregulation of the rail industry, which led to reduced rail prices, the cost of transporting low-sulfur coal from the West to power generation plants in the Mid-West became feasible (Ellerman et al. 2000). Thus, low-sulfur coal became a financially viable emission-reduction strategy and was adopted for use by some power plants. The fact that this coal had lower heating values resulted in lower overall electricity generation efficiencies, as measured in kWh of electricity produced per kg of coal used.

[g] 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 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 moving away from the use of oil for this purpose.

[h] In the case of natural gas, government price regulation of natural gas in the 1950s and 60s led to declining production and increased 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 mentioned above, brought about an overall decline in electricity generation from natural gas during the 1970s and 80s. 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.

Figure 8 shows the efficiency of aircraft travel and the production of revenue passenger kilometers (RPK). Efficiency is measured in terms of RPK produced per joule of energy, while production is measured in RPK produced. As in the majority of the above plots, efficiency and production again increase in parallel.

The correlation between production and efficiency can be clearly demonstrated by directly plotting production versus efficiency. Figures 9 through 16 provide such plots for the industrial activities shown in Figures 1 through 8. While periods of volatility do exist, particularly in the electricity generation industry, the overall trend across these industrial activities does seem clear; production and efficiency have a strong positive correlation.

While the efficiency trends shown in Figures 1 through 8 speak highly for the ability of society to continuously improve technology over time, Figures 17 through 24, show that despite tremendous improvements in efficiency, the impact of each of these industries has continued to increase over time.

Table 1 summarizes the average annual changes in production ($\Delta P/P$) and the average annual changes in efficiency ($\Delta e/e$) for the five industrial sectors analyzed in Figures 1 through 24. Positive values for changes in production indicate production increases, while positive values for changes in efficiencies indicate efficiency improvements. The data clearly shows that in each of these industries, the average annual $\Delta P/P$ exceeded the average annual $\Delta e/e$, meaning that, on average, equation (2) was not satisfied.

The values in Table 1 can also be shown graphically by plotting the average annual change in productivity versus the average annual change in efficiency. Such a plot appears in Figure 25. The solid diagonal line shown in Figure 25 is the line of constant impact. It represents the condition in which the average annual $\Delta P/P$ is equal to the average annual $\Delta e/e$. Thus, points above this line represent periods of increasing impact, where equation (2) is not satisfied, while points below this line represent periods of decreasing impact, where equation (2) is satisfied. The points shown in Figure 25 represent average values, as shown in Table 1; the error bars represent plus or minus one standard deviation.

Causality

While the data presented above shows a strong *correlation* between production and resource efficiency, there also exists the possibility of a *causal* relationship between the two. As early as 1865, W. Stanley Jevons observed that more efficient coal mining led to more coal production and consumption, not less. As 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 hypothesis, that improved efficiency could in fact stimulate more production and consumption rather than less, has been alternately called "Jevons' Paradox", the "rebound effect" and/or the "take back effect" (Herring 1998, Alcott 2005, Hertwich 2005). More recently, this idea has come under intense scrutiny in the energy policy literature, as efficiency measures have been proposed to meet CO_2 emission targets set forth in the Kyoto Protocol (Herring 1998, 2006).

The mechanisms responsible for this efficiency take back effect can be found in basic neo-classical economic theory. At the micro level, efficiency can lead to savings and price reductions, which, if there is sufficient price elasticity of demand, can lead in turn to increased demand. This increase can be decomposed into two elements: 1) a substitution effect which moves along an indifference curve, and 2) an income effect which moves to a higher utility (Lovell 2004, Pindyck and Rubinfeld 2001)

Recent measurements of the microeconomic take back effect have revealed a very large range in values, depending on the economic actor, the service provided, and the length of time since the efficiency improvement. For example, in a survey of measured rebound effects in the U.S. by Greening et al., appliances or "white goods" showed essentially 0% rebound, residential lighting showed 5 to 12% rebound, and space cooling showed 0 to 50% rebound (Greening 2000). On the other hand, Roy found kerosene use (with a restricted supply) for lighting and cooking in rural India to have a rebound effect well near 100% and, in some cases, up to 200% (Roy 2000). In general, larger take back effects are found among lower-income populations for commodities with a high price elasticity of demand. Also relevant to this discussion is work by Bentzen, who estimated the take back for energy efficiency in the U.S. manufacturing sector based upon measurements of own price elasticities (2004). During times of declining energy prices, the rebound was estimated to be 24%, while during times of price recovery, the rebound was estimated to be 52% (Bentzen 2004).

At the macroeconomic level, the resource efficiency effect can be represented in growth theory by the factor substitution effect. Efficiency reduces the price of one factor, which, dependent on the elasticity of substitution, can then be substituted for the other factors. This view has been formalized as the “Khazzom-Brookes Postulate” by Saunders, and has been vigorously debated in the energy and energy policy literature (Saunders 1992, Khazzom 1987, Lovins 1988, Brooks 1992, 1993, Grubb 1990, 1992, Herring 1998). In general, many engineers and technology optimists support efficiency as an effective conservation mechanism, while most economists doubt its effectiveness (Herring 1998, 2006). While the many recent measurements mentioned above have helped to quantify and clarify some of the issues of the microeconomic debate, the macro level debate has continued largely at the theoretical level (Saunders 1992, 2000a, 2000b, Howarth 1997). The prototypical causality argument at the macro level, in broad strokes, is that efficiency provides savings that can be invested and/or spent. Either way, these promote economic activity and growth, thereby stimulating production and resource use.

Hence, the energy debate essentially comes down to the role of energy efficiency in economic growth. From a historical perspective, this question is relatively new to economic growth theory, which focuses almost exclusively on capital and labor, and more recently on technology innovation, as the primary factors of production (Solow 1956, Barro 2004, Daly 2004, Stern 2004). Energy inputs, per se, are not given an explicit role in the formulations of the standard growth theories. Suggestions on alternative formulations have been made, but are new and largely untested (Georgescu-Roegen 1971, Daly 2004, Ayres 2005). Given both the infancy and the complexity of this debate, it is likely that there will be much more to discuss, particularly as modeling efforts become more sophisticated and better track empirical observations (Ayres 2005).

In the meantime, it seems likely that some amount of rebound is potentially present in almost every efficiency effort. At the same time, identifying the rebound effect as the sole factor responsible for the significant growth that is shown here seems overstated. Certainly from the view of the manufacturing firm, there are many additional incentives to increase production (and resource use) in addition to the increased demand stemming from lower prices derived from increased efficiency. The key insight appears to be that efficiency is part of an ongoing dynamic that helps promote additional growth. The size of this effect is likely to be debated for many years, and may never be definitively quantified because the necessary experiment, to run the economy both with and without efficiency improvements, seems highly unlikely to occur.

Consumption and Policy-driven Efficiency

While the analysis of efficiency and production data for the five industrial sectors presented above show increases in production outpacing improvements in efficiency, cases do exist in which a different dynamic plays out. Figures 26 through 33 present the cases of automobiles and refrigerators, cases in which government-mandated efficiency improvements led to different trends in efficiency and production. These two cases also differ in that while the previous cases focused primarily on efficiency during the manufacturing or production phase, the data for automobiles and refrigerators focuses on efficiency during the use or consumption phase.

Figure 26 shows efficiency and consumption data for automobiles in the United States. Efficiency is measured in miles traveled per gallon of gasoline used, while consumption is measured in vehicle-miles. The efficiency data for automobiles shows an extended period of declining efficiency[i], followed by an approximately 20-year period of improving efficiency[j], and, most recently, a decade of relatively static efficiency[k]. These

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[i] The original period of declining efficiency was due in large part to market demands, as an increasingly affluent post-World War II public demanded larger, more powerful cars with more accessories (Hirsh 1999).

[j] The period of improving efficiency, which began in the mid-1970s and ran until the early 1990s, was brought about by both market and legislative drivers. The oil crises of the 1970s introduced gasoline availability concerns and higher gasoline prices to drivers in America, thereby stimulating American consumer interest in improved 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 automobiles, also drove carmakers to improve automobile fuel efficiency. Combined, these factors had a noticeable effect on automobile efficiency in the United States.

efficiency trends were driven by many factors, including market demand, oil supply, and government legislation in the form of Corporate Average Fuel Economy (CAFE) standards. Meanwhile, consumption of vehicle-miles has increased considerably, as more Americans drive more.

Figure 27 shows efficiency and consumption data for residential refrigerators in the U.S. The efficiency trends for refrigerators mimic, to some degree, the efficiency trends of automobiles. Prior to the late 1970s, refrigerator efficiency, as measured in hours of refrigeration per kWh of electricity used, decreased steadily[l]. However, after this period, efficiency improved considerably, driven primarily by state and federal efficiency regulations on appliances[m]. At the same time, consumption of refrigeration hours has increased with time, as more American households use more hours of refrigeration.[n]

Figures 28 and 29 plot consumption versus efficiency for both automobiles and refrigerators. From these plots, the periods of negative correlation, positive correlation, and no correlation, in the case of automobiles, are apparent. Figures 30 and 31 show drastically different impact trajectories for automobiles and refrigerators. In the case of automobiles, the impact, as measured in gallons of fuel used, continued to increase, despite efficiency improvements. Figure 31 shows a different dynamic, one in which efficiency improvements for refrigerators were able to outpace increases in consumption.

The effect of regulations on the efficiency of automobiles and refrigerators, and, in turn, the effect of these efficiency improvements on total impact, provides important lessons. In both cases, efficiency improvements were legislated. However while refrigerator

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[k] The recent “stabilization” of automobile efficiency is due in part to the fact that CAFE standards have not been updated for over a decade. Consumer demand for larger vehicles and better performance has also contributed to this plateau in fuel efficiency.

[l] This decrease in efficiency was due to various factors, including additional refrigerator features and increased refrigerator size.

[m] 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 (USDOE 2004). Since then, the efficiency standards for refrigerators have been updated multiple times, ensuring that efficiency improvements continue (IEA/OECD 2003).

[n] While the number of hours of refrigeration an individual refrigerator provides is 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.

legislation was frequently updated, automobile legislation was not. In a decade-by-decade analysis, as shown in Figures 32 and 33, the effect of these different approaches is clear. These plots, much like figure 25, plot the average annual change in consumption ($\Delta C/C$) versus the average annual $\Delta e/e$. However, unlike Figure 25, the data from each decade is averaged separately, thus providing a time progression. The solid diagonal line shown in Figures 32 and 33, as in Figure 25, represents the condition in which the average annual $\Delta C/C$ is equal to the average annual $\Delta e/e$.

Figure 32 shows a time progression for automobiles. In the 1940s, 50s and 60s, efficiency was worsening, as shown by the negative change in efficiency values, and consumption was growing. Starting in the 1970s and continuing into the 1980s, efficiency began to improve considerably, reversing the trend of declining efficiency and showing significant improvements. However, in the 1990s, with no updates to the CAFE

standards and a relatively secure gasoline supply and price, efficiency improvements fell considerably in magnitude, moving away from the constant impact line. While the efficiency improvements of the 1970s and 80s had shown promise, failure to update legislation, among other causes, led to the return of previous dynamics.

Unlike the case of automobiles, refrigerators did succeed in crossing the line of constant impact. In the 1950s and 60s, refrigerator efficiency was worsening. However, with regulations beginning to take effect in the 1970s, the efficiency of the fleet of refrigerators in use slowly began to improve. In the 1970s and 80s, significant efficiency improvements were realized, moving refrigerators past the constant impact line for the first time. This trend continued into the 1990s, in large part due to constantly updated efficiency requirements. Crossing over the constant impact line, as refrigerators did in the 1980s, meant that the overall impact of refrigerators actually declined. Of the cases shown in this paper, refrigerators, specifically refrigerators in the 1980s and 1990s, were the only example in which equation (2) was satisfied. In all other cases, increases in production and consumption outpaced improvements in efficiency.

The fact that efficiency improvements for refrigerators successfully outpaced consumption can be seen as validation for a program of constantly-updated efficiency requirements. However, it is also important to point out that refrigerators fall into a category of products, that being appliances or “white goods”, in which the measured rebound has been found to be minimal (Greening et al. 2000). Despite this, the rebound effect is but one of many factors that contributes to a growth in consumption. Thus, the fact that efficiency improvements in refrigerators were able to outpace consumption increases for an extended period of time is still notable.

Conclusions

This historical review provides little evidence that "naturally occurring" efficiency improvements alone can outpace production increases and lead to an overall reduction in resource use. In fact, of the seven cases examined here, only one, refrigerator use, showed an absolute decrease in energy usage, and then only because of policy intervention. While improving efficiency can lead to higher levels of goods and services for society and associated improvements in one's standard of living, there is no historical evidence that it leads to conservation. Under these circumstances, efficiency improvements could be best thought of as a "necessary but insufficient" step towards sustainability. Improved efficiency is necessary to provide the essential goods and services that are needed by the developing world. That it is insufficient has been demonstrated so far by history.

From the point of view of a manufacturing firm, it is quite clear that a value proposition, external to the firm, is required to promote real conservation. This paper presents evidence for the effectiveness of one type of "external value proposition", namely government-regulated efficiency standards. However, many other external value propositions exist which could be effective. These range from increased resource pricing by a variety of mechanisms including taxation, to strengthened consumer buying preferences, perhaps through increased awareness. It does seem clear from the historical record that relying on "naturally occurring" efficiency improvements, or on voluntary uneconomic behavior by firms, is not a realistic means of reducing resource consumption. At the same time it is important to note that the future will not be a linear extrapolation of the past. Reducing resource use could be brought on by a variety of mechanisms not addressed in this paper, nor evidenced in the historical record presented here.

To be sustainable in the long run, the resource of which there exists a large and continuous supply, namely energy, must be substituted for those resources which are limited. Ironically, it is precisely a large elasticity of energy substitution for other factors of production that leads to a very large rebound effect. Of course, the large and continuous supply of energy comes not from fossil fuels, but rather from the sun.

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Table and Figures

FIGURE 1: Worldwide Pig Iron Production (P) and the Energy Efficiency of Pig Iron Production (e) [1]

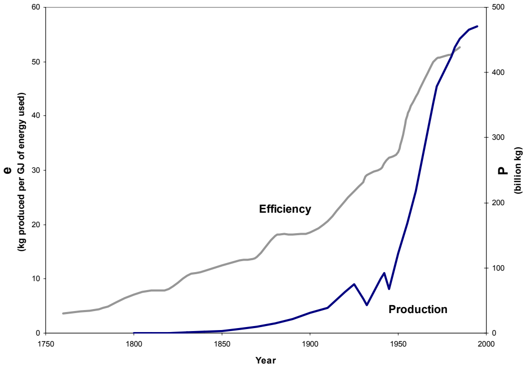


FIGURE 2: Worldwide Pig Iron Production (P) and the Efficiency of Coke Usage in Pig Iron Production (e) [1]

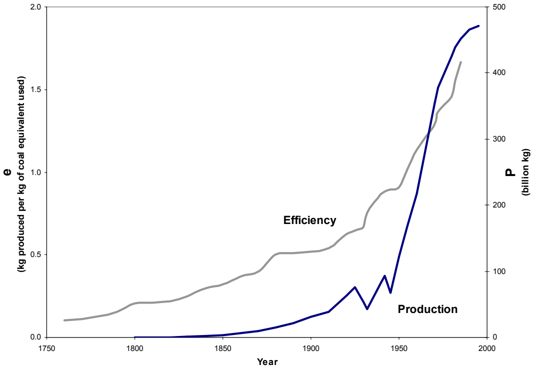


FIGURE 3: Worldwide Primary Aluminum Production (P) and the Energy Efficiency of Aluminum Production (e) [2]

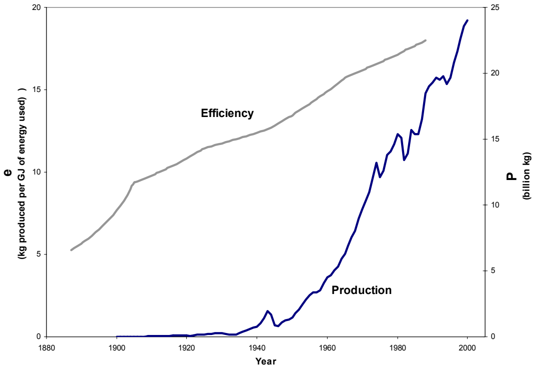


FIGURE 4: Worldwide Nitrogen Fertilizer Production (P) and the Energy Efficiency of Ammonia Synthesis (e) [3]

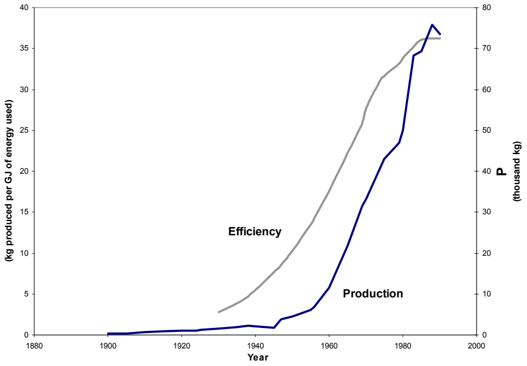


FIGURE 5: Electricity Generation from Coal (P) and the Efficiency of Electricity Generation from Coal (e) (US data) [4]

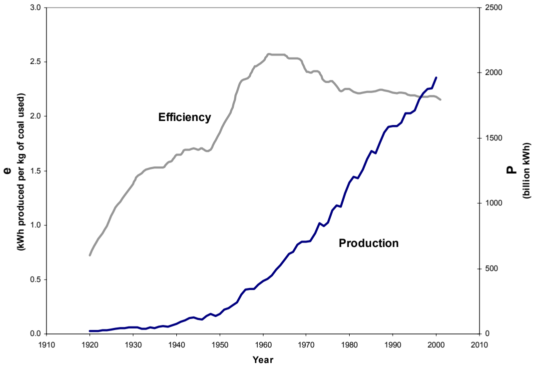


FIGURE 6: Electricity Generation from Oil (P) and the Efficiency of Electricity Generation from Oil (e) (US data) [4]

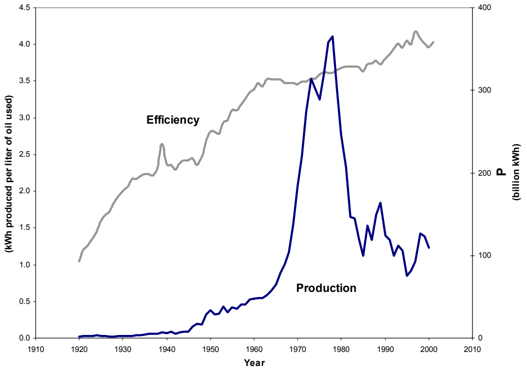


FIGURE 7: Electricity Generation from Natural Gas (P) and the Efficiency of Electricity Generation from Natural Gas (e) (US data) [4]

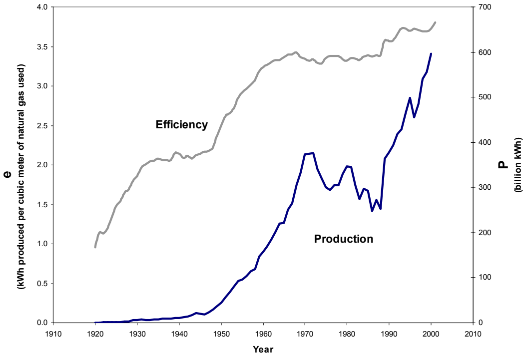


FIGURE 8: Revenue Passenger Kilometer (RPK) Production (P) and the Energy Efficiency of Aircraft Travel (e) (US data) [5]

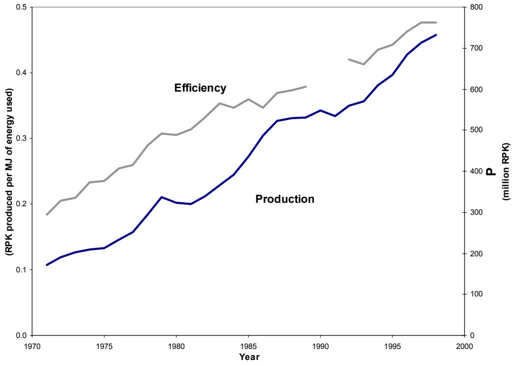


FIGURE 9: Worldwide Pig Iron Production (P) versus the Energy Efficiency of Pig Iron Production (e) [1]

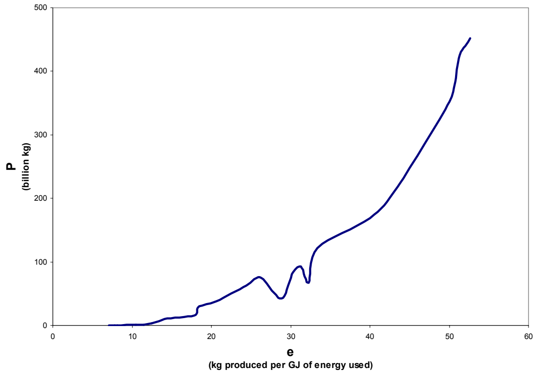


FIGURE 10: Worldwide Pig Iron Production (P) versus the Efficiency of Coke Usage in Pig Iron Production (e) [1]

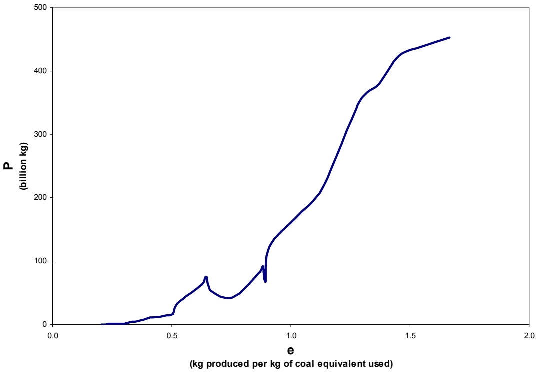


FIGURE 11: Worldwide Primary Aluminum Production (P) versus the Energy Efficiency of Aluminum Production (e) [2]

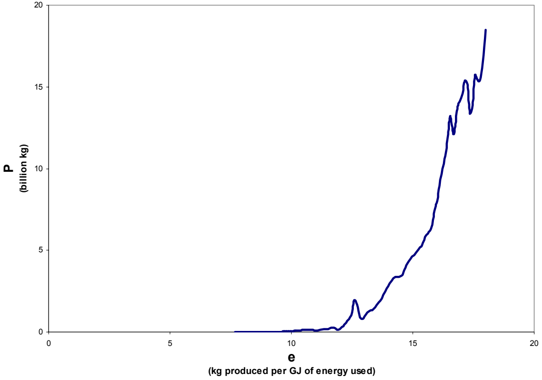


FIGURE 12: Worldwide Nitrogen Fertilizer Production (P) versus the Energy Efficiency of Ammonia Synthesis (e) [3]

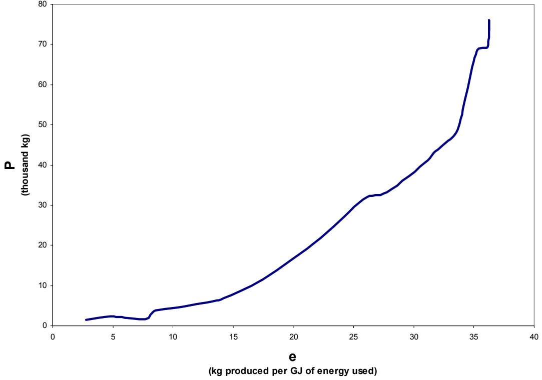


FIGURE 13: Electricity Generation from Coal (P) versus the Efficiency of Electricity Generation from Coal (e) (US data) [4]

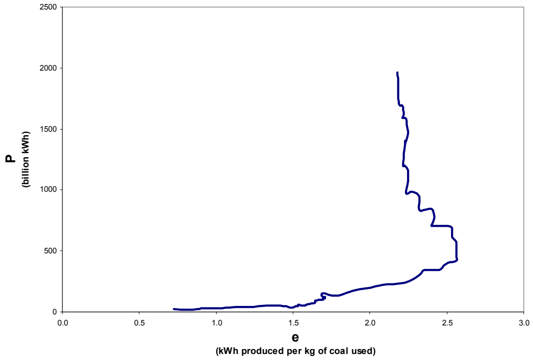


FIGURE 14: Electricity Generation from Oil (P) versus the Efficiency of Electricity Generation from Oil (e) (US data) [4]

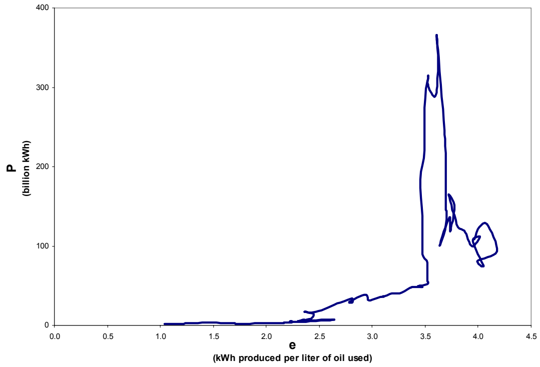


FIGURE 15: Electricity Generation from Natural Gas (P) versus the Efficiency of Electricity Generation from Natural Gas (e) (US data) [4]

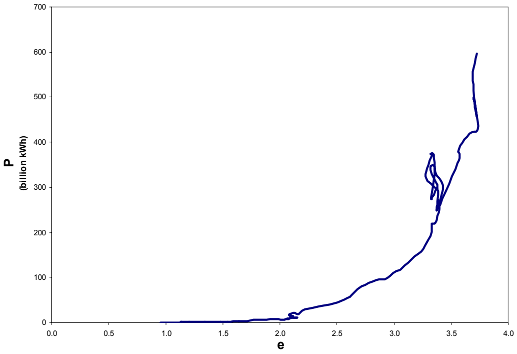


FIGURE 16: Revenue Passenger Kilometer (RPK) Production (P) versus the Efficiency of Aircraft Travel (e) (US data) [5]

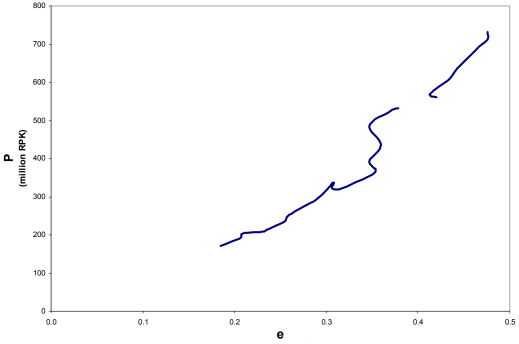


FIGURE 17: Impact (I) of Worldwide Pig Iron Production (Energy) [1]

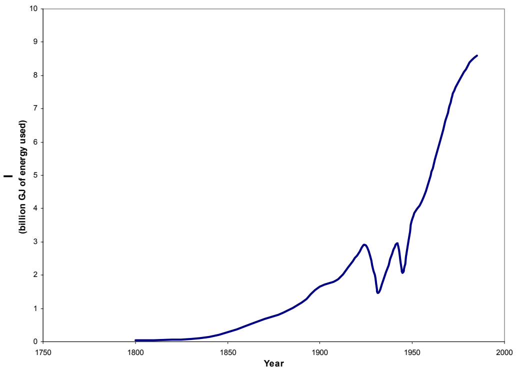


FIGURE 18: Impact (I) of Worldwide Pig Iron Production (Coke) [1]

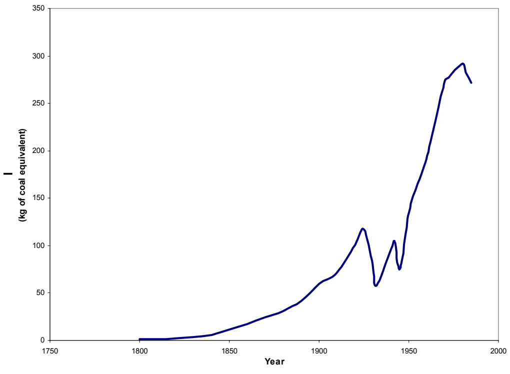


FIGURE 19: Impact (I) of Worldwide Primary Aluminum Production [2]

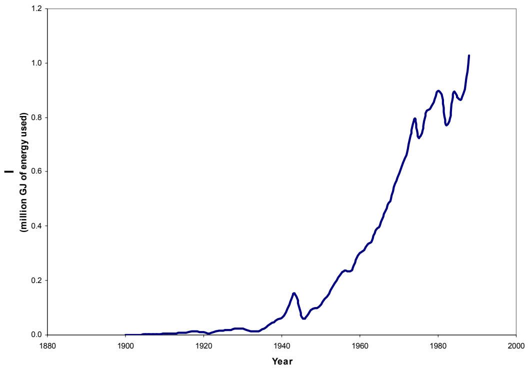


FIGURE 20: Impact (I) of Worldwide Nitrogen Fertilizer Production [3]

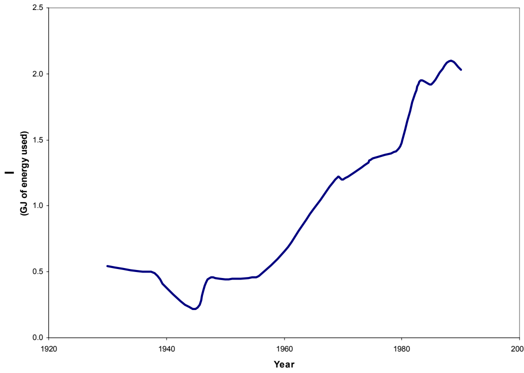


FIGURE 21: Impact (I) of Electricity Generation from Coal (US data) [4]

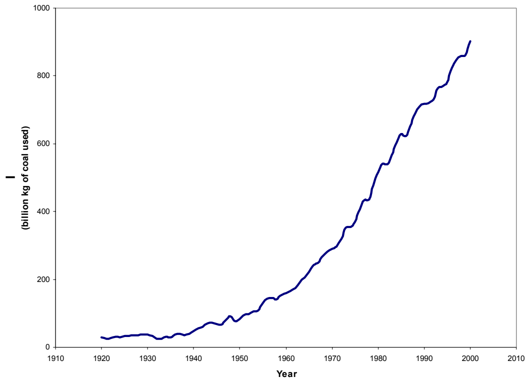


FIGURE 22: Impact (I) of Electricity Generation from Oil (US data) [4]

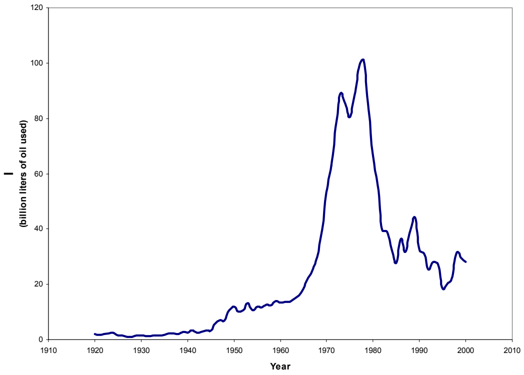


FIGURE 23: Impact (I) of Electricity Generation from Natural Gas (US data) [4]

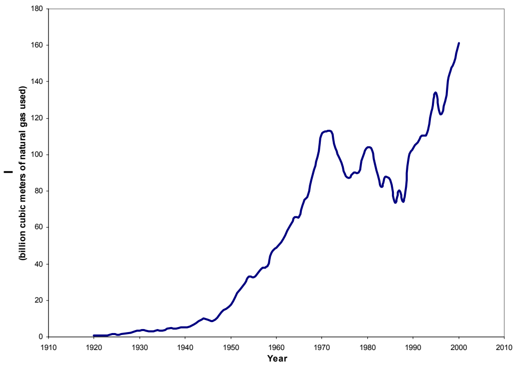
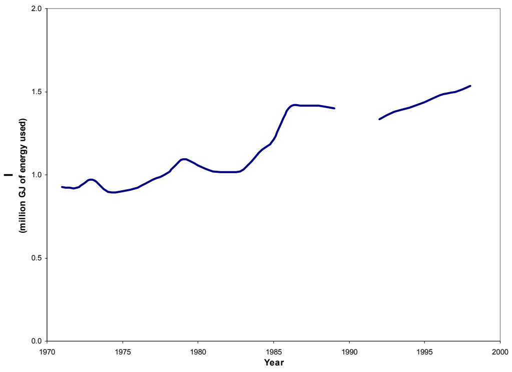


FIGURE 24: Impact (I) of Aircraft Travel (US data) [5]



Product	Time Period (years)	Average Annual ΔP/P	Average Annual Δe/e	Average ΔP/P / Average Δe/e
Pig Iron				
Energy use	1800-1984	4.1%	1.1%	3.7
Coke use	1800-1984	4.1%	1.1%	3.6
Aluminum				
Energy use	1900-1987	11.1%	1.0%	11.4
Nitrogen Fertilizer				
Energy use	1930-1989	7.1%	4.4%	1.6
Electricity				
Coal	1920-2000	4.6%	1.4%	3.3
Oil	1920-2000	5.3%	1.7%	3.0
Natural Gas	1920-2000	7.8%	1.8%	4.4
Air Travel				
Energy use	1971-1988, 1992-1997	6.1%	3.7%	1.7

Table 1: Average annual ΔP/P, average annual Δe/e, and the ratio of the two for five industrial sectors over different time periods. In each case, increases in production outpace improvements in efficiency by factors ranging from 1.6 to 11.4

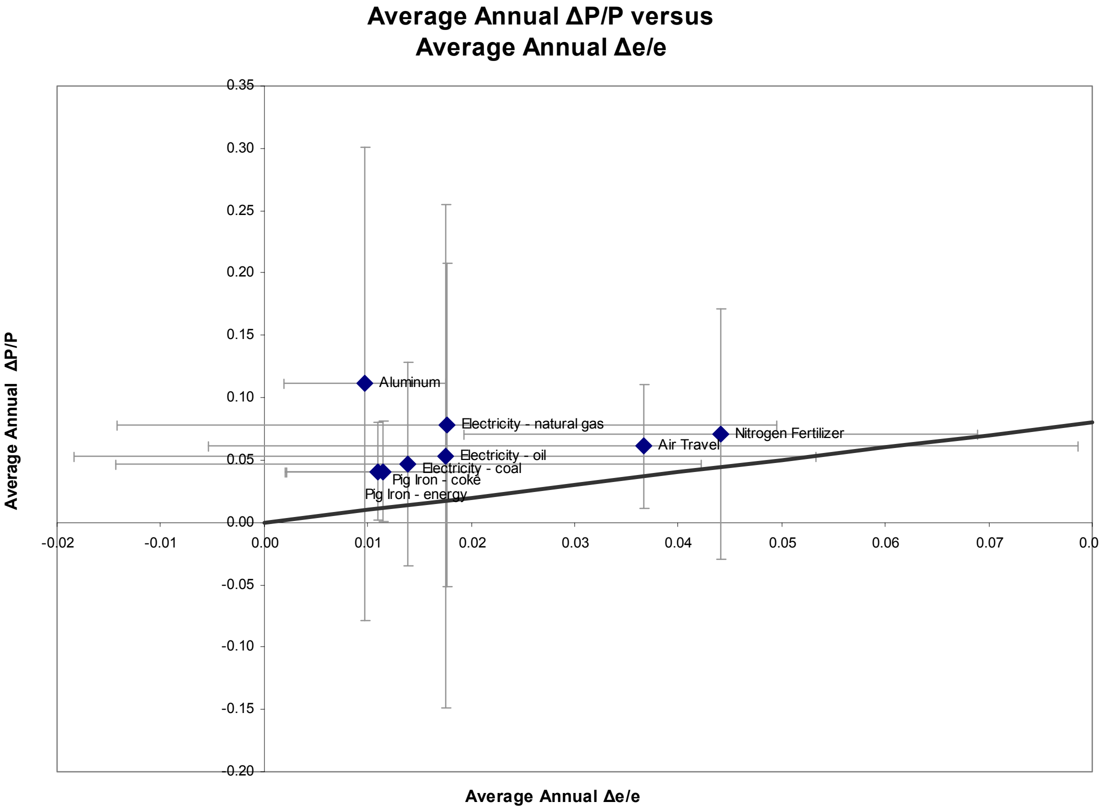


Figure 25: Average annual ΔP/P versus average annual Δe/e for five industrial sectors.

FIGURE 26: Miles of Automobile Travel Consumed and the Efficiency of Automobile Travel (US data) [6]

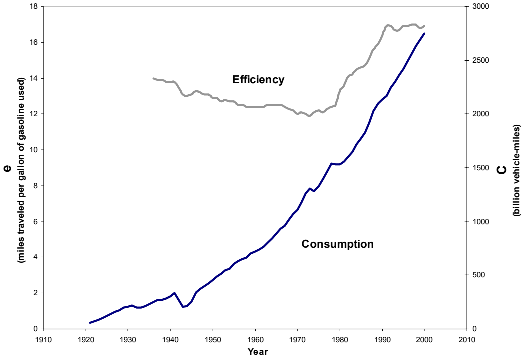


FIGURE 27: Hours of Refrigeration Consumed and the Efficiency of Refrigerators (US data) [7]

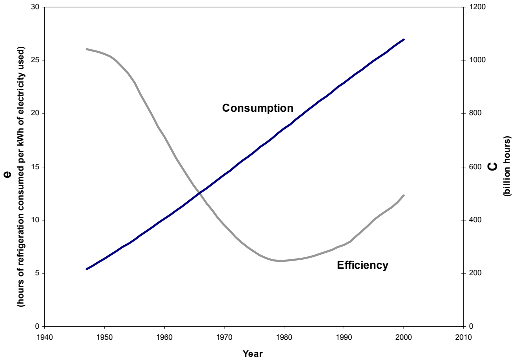


FIGURE 28: Miles of Automobile Travel Produced versus the Efficiency of Automobile Travel (US data) [6]

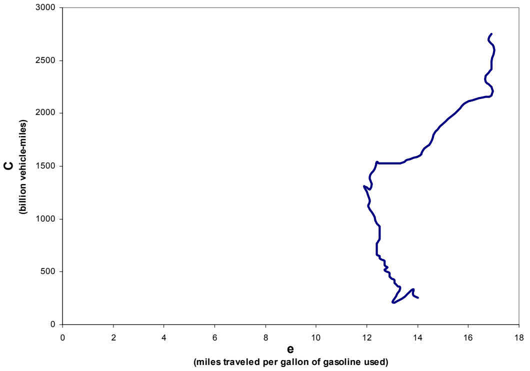


FIGURE 29: Hours of Refrigeration Consumed versus the Efficiency of Refrigerators (US data) [7]

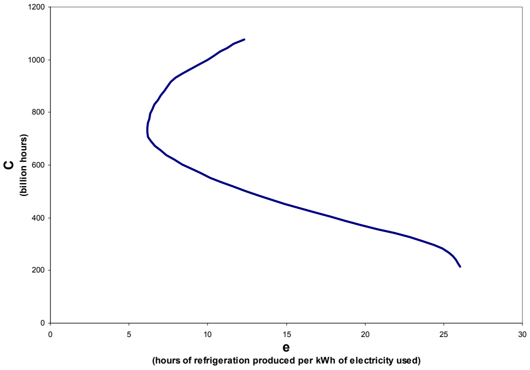


FIGURE 30: Impact of Automobile Travel (US data) [6]

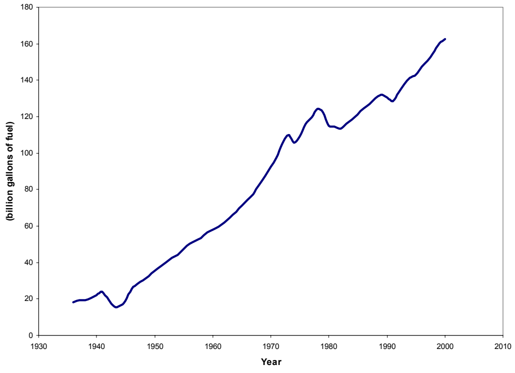


FIGURE 31: Impact of Refrigerator Use [7]

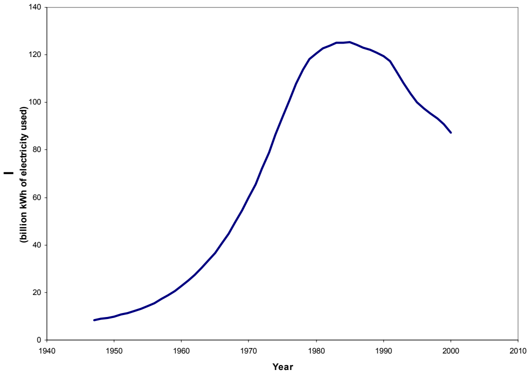


FIGURE 32: Average Annual ΔC/C versus Average Annual Δe/e for Automobiles (US data) [6]

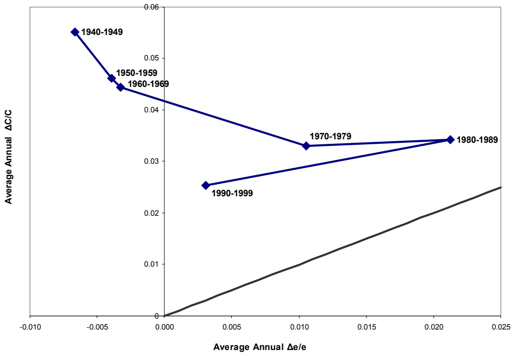
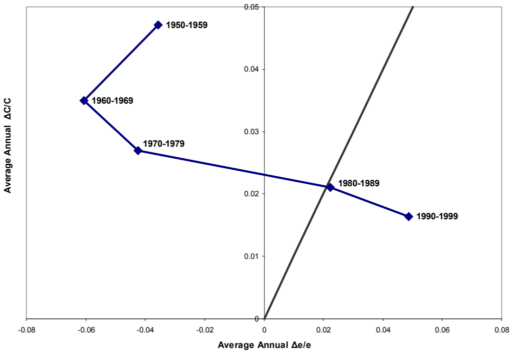


FIGURE 33: Average Annual ΔC/C versus Average Annual Δe/e for Refrigerators (US data) [7]



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