LIGHTING ELECTRICITY STEEL

ENERGY EFFICIENCY BACKFIRE IN EMERGING ECONOMIES

by Max Luke, Amy Meyer, Ted Nordhaus, Harry Saunders, Michael Shellenberger, and Alex Trembath

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INTRODUCTION

For the first time in its 25-year history, in April 2014 the Intergovernmental Panel on Climate Change (IPCC) affirmed that energy efficiency measures can lead to increases in demand for energy, thereby diminishing the reductions to carbon emissions precipitated by energy efficiency measures. The so-called rebound effect "cannot be ignored," wrote the authors of the *Mitigation of Climate Change*[1] report, which reviewed the best available peer-reviewed literature on the topic.

While it has long been known that cost-effective energy efficiency measures are beneficial to economic welfare and therefore worth pursuing on grounds other than climate change mitigation, the magnitude of rebound effects and their implications for the utility of energy efficiency as a climate change mitigation strategy remain contested. The IPCC's recognition of the importance of the rebound effect confirms previous work by Sorrell,[2] Jenkins et al.,[3] Chakravarty et al.,[4] Saunders,[5] and others who have argued that rebound effects are real and can be significant in a variety of contexts. However, the extent to which rebound effects from specific sectors and economic contexts can be generalized across other sectors and economies remains debated. Much of the research to date has been theoretical or specific to a given sector, and it remains unclear how important rebound effects are on an economy-wide scale.

Over the past several years, researchers have attempted to fill the gaps in this literature. Some have focused on reviewing previous literature on the topic,[3,4,6] while others have modeled rebound effects or reviewed historical evidence of the rebound effect in action.[5] While this research has improved our understanding of the potential magnitude and implications of the rebound effect, it has not fully elaborated the mechanics of how and why rebound actually occurs.

This report attempts to provide insight into these questions by offering three case studies on historical instances of rebound: electricity production in twentieth-century America, lighting from 1700 to the present, and historical iron and steel production. These cases are of particular relevance to energy and climate change policy because each of these sectors is expected to be a major driver of future energy demand and therefore greenhouse gas emissions. Electricity generation comprises 18 percent of the world's total energy consumption, a share that is expected to grow. Lighting is one of the largest end-users of electricity globally, comprising 19 percent of total global electricity use.[7] And the iron and steel sector is one of the largest industrial consumers of energy.[8]

Introduction

Several common characteristics link the three case studies. In each case, demand for new energy services and energy-intensive goods was far from saturated, and occurred in the context of rapid industrialization and growth. Additionally, in each case the introduction of more energy efficient technologies contributed to significant cost declines, enabling the widespread use of energy services that enhanced human welfare. In all three cases, more energy efficient technologies produced rebound effects and ultimately contributed to a net increase in energy demand, or "backfire."

Energy Demand

	Percent of Final Energy Demand
Lighting	4.3% (2005)
Electricity	17.7% (2011)
Steel	8.1% (2005)

Source: Calculated by Jessica Lovering, policy analyst, Breakthrough Institute, based on IEA and Earth Policy Institute data.[7]

The implications of these case studies are not that energy efficiency improvements will lead to backfire in every context, nor that other trends, such as rising incomes and population growth, were less important than efficiency improvements in the growth in energy consumption. Nor do they suggest that the overall effects of energy efficiency measures in these industries were undesirable. On the contrary, the economic implications of rebound and backfire are far from negative, both in these specific cases and in general. Energy efficiency gains reduce the cost of important energy services such as lighting, heating, and transportation, thus enabling their consumption in greater quantities and, by extension, contributing to economic and social welfare.

Introduction

These studies do suggest, however, that in industrial and commercial sectors, and particularly in industrializing economies in which there is large unmet demand for energy services and ample room for growth, there is a high likelihood of rebound effects and a distinct possibility for backfire. As the IPCC notes, there is "evidence to support the claim that rebound effects can be higher in developing countries." For example, the report highlights, "rebound effects in the residential sector in India and other developing countries can be expected to be larger than in developed economies because high-quality energy use is still small in households in India and demand is very elastic." The likelihood that rebound will be even higher in the developing world than in the developed world, where the IPCC finds a rebound effect of 20 to 45 percent in end-use technologies, underscores the need for further research into the mechanics of the rebound effect and its likely economy-wide impact. In the IPCC's words, more research will be essential to establish "a clearer understanding of [efficiency's] contribution to climate policy."[1]

It is in this spirit that the following case studies are offered. By highlighting the mechanisms through which the rebound effect has occurred across three important, energy- and emissions-intensive industries, these case studies illustrate the importance of rebound effects and point out several factors suggesting that they will be experienced in significant measure in the future, in particular in emerging world economies. Policy makers would be well served to think carefully about how heavily we should depend on efficiency-related emissions reductions in these and similar sectors of the global economy, the report concludes.

A CASE STUDY IN LIGHTING

In the United Kingdom, per capita lighting consumption from electricity jumped four orders of magnitude in 200 years, from 1,000 lumen-hours in 1800 to more than 13 million lumen-hours in 2000.[14]

Lighting technologies have been a fixture of human development since the discovery of the controlled open flame, which allowed humans to live, prepare food, and communicate in profoundly new ways. The importance of lighting can be seen in the amount that we spend on it. Over the past three centuries since 1700, the world spent 0.7 percent of its gross domestic product (GDP) on light. And since 1700, lighting has predictably accounted for about 6.5 percent of the world's total consumption of primary energy.[9]

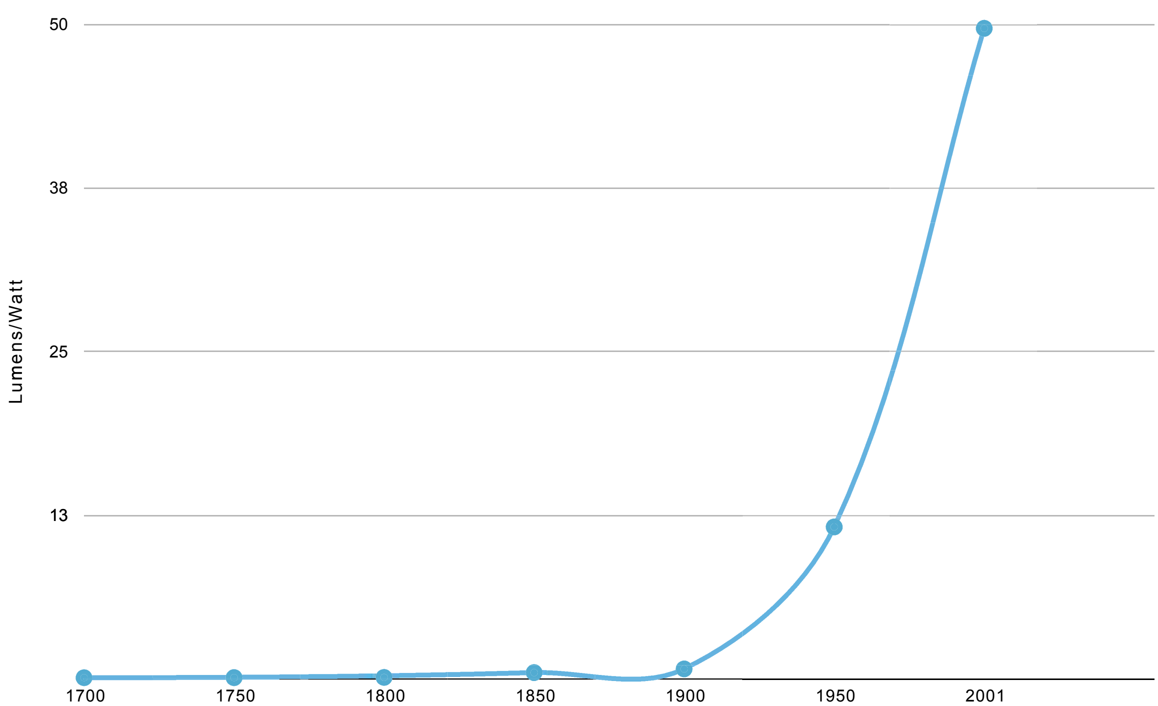
It is perhaps unsurprising, then, that as the energy efficiency of lighting has increased several hundred-fold since the year 1700, increased demand for energy used in lighting has offset any energy savings that might have occurred. While population growth and rising incomes contributed to this increase, such demand growth would not have been possible without the introduction of more energy-energy-efficient lighting technologies.[9-12] Historical backfire in lighting is largely a result of efficiency gains creating opportunities for new products, applications, and whole new industries. From candles to kerosene and electricity, as lighting technologies have become more efficient and more affordable, societies have been very creative in finding new ways to use them, leading to more overall energy consumption.

Lighting

FROM FLAME TO FILAMENT: HOW EFFICIENCY HELPED ILLUMINATE THE WORLD

Open fire is the earliest and least energy-efficient form of illumination, and early humans quickly found more-efficient modes of illumination. The invention of the wick, which was first used in ancient oil lamps, allowed for targeted control when burning fuel. The wick also enabled fuels to be gradually utilized, conserving energy and improving the efficiency of illumination. Over time, wicks came to be used with waxy substances, which provided a slower, more efficient burn than oil. The birth of the candle more than 5,000 years ago marked a major innovation in the history of illumination. Candles provided illumination for less energy than the early oil lamps they replaced.[13]

Lighting Efficiency

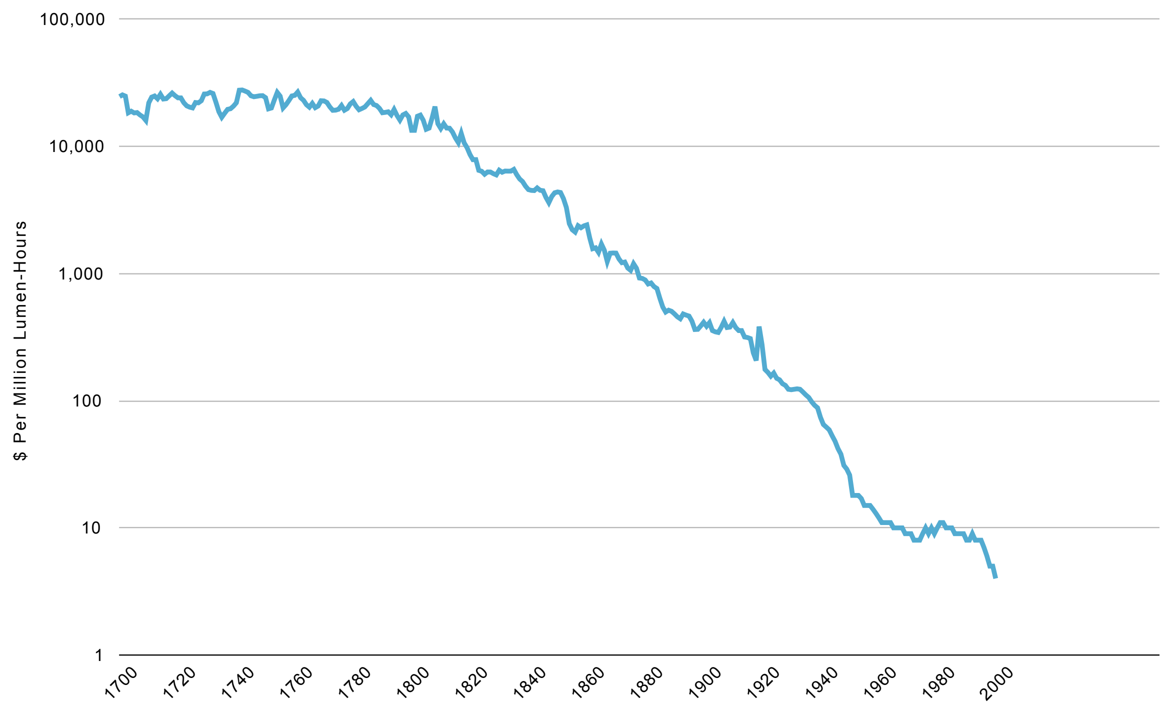


Source: Tsao and Waide (2010)

In the past three centuries, from 1700 to 2000, we've moved from primarily using tallow candles to the use of high-efficiency incandescent and compact fluorescent lighting. Continuous innovation in lighting technologies has driven an increase in the energy efficiency of illumination by a factor of 900.[13]

Tallow candles, which produced 0.076 lumens per watt (lm/W), were the dominant form of illumination from 1700 until well into the nineteenth century.[13] Energy efficiency improvements in the 1700s helped reduce the average cost of lighting in that century by nearly 50 percent, from $24,600 per million lumen-hours to $13,300 per million lumen-hours.[14] Energy economists Roger Fouquet and Peter Pearson found that the price elasticity of demand for lighting in the 1700s (that is, the amount that people adjust their lighting demand in response to changes in price) was less than -1, indicating that such cost reductions led to a net increase in lighting consumption.[12]

Price of Lighting

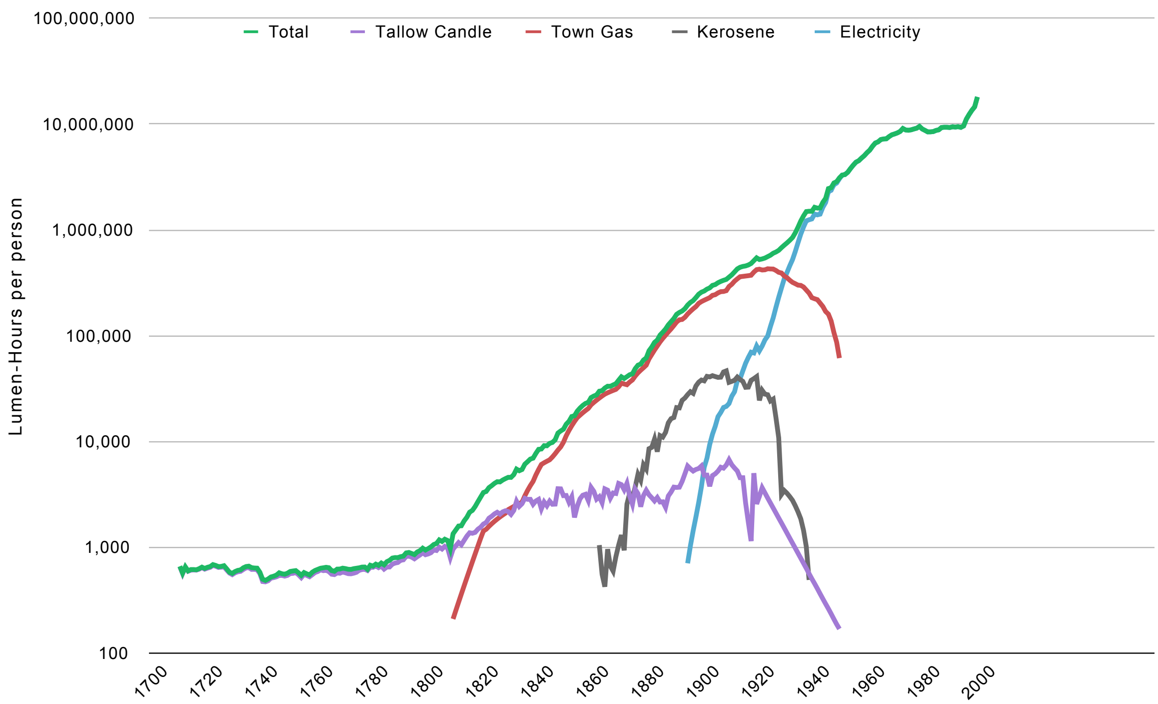


Source: Fouquet and Pearson (2006)

Energy efficiency improvements in lighting technologies (as well as declining fuel prices) contributed to a dramatic decline in the cost of energy services. Between 1700 and 2000, the average price of lighting services in the United Kingdom declined by 99.98 percent.[14]

The increasing affordability and availability of lighting contributed to technological innovation, and in the early 1800s, William Murdock successfully commercialized a new lighting technology, town gas. The first commercial town gas lamps in the 1820s were nearly twice as energy efficient as the candles they replaced, producing 0.13 lm/W.[13] Efficiency improvements in the lighting sector in the 1800s, led largely by an increase in town gas, contributed to significant cost declines. Between 1800 and 1850 the average price of lighting services in the United Kingdom declined by 67 percent.[14] Reductions in the cost of lighting services, coupled with the growing affluence of the British, led to a rapid increase in the per capita consumption of lighting services. Between 1800 and 1850, per capita lighting consumption in the UK increased from 940 lumen-hours to 13,000 lumen-hours, and during this period, Fouquet and Pearson found empirical econometric evidence for backfire.[14]

Per Capita Consumption of Lighting



Source: Fouquet and Pearson (2006) and Maddison (2010)

As costs declined, making lighting more affordable and promoting further innovation in new lighting technologies, the per capita consumption of lighting skyrocketed. Between 1800 and 2000, the per capita consumption of lighting in the United Kingdom increased by a factor of 11,800.[14]

By the early 1850s, as town gas was gaining popularity in England, experiments were being done to refine kerosene from crude oil. Benjamin Silliman Jr., a chemistry professor at Yale University, was the first to successfully fractionate petroleum by distillation, creating kerosene.[13] While full market penetration took some time, kerosene was far superior to many of its predecessors. It led to the displacement of whale oil lamps and provided a direct competitor to town gas.[14]

Lighting

Despite these improvements in kerosene-based lighting, town gas remained a dominant market player. A new generation of lamps had greatly improved their efficiency: by the late nineteenth century town gas produced 0.60 lm/W.[12] Continued efficiency improvements and cost declines led to the invention of the incandescent mantle, which, by the early twentieth century, increased the efficiency of the lamp to 0.87 lm/W, contributing to even further cost reductions and greater uptake. The resulting efficiency improvements helped reduce the cost of illumination from gas burners from over $600 per million lumen-hours in 1850 to $150 per million lumen-hours by 1900.[14] Between 1850 and 1900 the per capita consumption of light from town gas lamps in the UK increased from 9,850 lumen-hours to 210,200 lumen-hours — a 21-fold increase.[14] Fouquet and Pearson found that the period between 1850 and 1900 was especially conducive to backfire. For most of this period, the price elasticity of demand for lighting services was near or below –1.5, meaning that for every unit decline in the price of lighting, the demand for more lighting would increase by 1.5 units.[12]

But the rapid increase in the use of town gas and kerosene — partly enabled by efficiency improvements and dramatic cost reductions — was only a prelude to a technology that would permanently transform illumination: electricity.

In 1802, Humphry Davy connected wires to a battery and a piece of carbon, producing a glowing filament.[15] The resulting glow was too bright for practical use and burned out quickly, but the arc lamp was the first step toward the modern lightbulb. In 1810, the arc lamp was premiered at the Royal Institution in London and employed for various outdoor events, but the design did not allow individual control or indoor use.[14] In 1840, Warren de la Rue achieved longer illumination by placing a platinum filament within a vacuum tube and passing an electric current through the system. Platinum has a high melting point and was predicted to have a longer lifetime. Platinum ultimately proved too expensive for commercialization, but the introduction of the evacuated chamber marked a significant innovation that enhanced the energy efficiency of the technology.[15]

In 1850, Joseph Wilson Swan, an English physicist, produced a lightbulb model that enclosed filaments made from carbonized paper in a vacuum chamber. At the time, vacuum technology was neither cheap nor good enough to successfully commercialize. Better vacuum pumps were introduced, and in 1878 Swan was able to create a better bulb.[15] In July 1874, four years before Swan's success, a Canadian patent was accepted for the first electric lightbulb. The bulb, invented by Henry Woodward and Mathew Evans, contained carbon rods situated between electrodes in glass cylinders that were pumped full of nitrogen. Woodward and Evans were unable to raise enough money to commercialize their bulb, and ultimately sold their patent to Thomas Edison in 1879. Edison had already created a bulb that could last 40 hours, and the new patent allowed him to improve on his original design. Edison sealed a carbon filament within a tube and connected it to platinum contact wires.[15]

Edison's carbon filament bulb was several times more efficient than the best kerosene and town gas lamps it would soon replace, generating 2.6 lm/W.[13] His initial accomplishments led him to found the Edison Electric Light Company in 1878, where he successfully commercialized his bulb. The General Electric Company formed in 1892 by merging Edison's company with the Thomson-Houston Company, and by 1910, iterations of Edison's initial carbon filament bulb achieved efficiencies of 6.5 lm/W.[13]

But the efficiency improvements didn't stop there. In 1909, General Electric's William Coolidge developed a ductile tungsten filament that dramatically increased the efficiency of Edison's bulb. Coolidge's tungsten filament bulb achieved efficiencies of 12 lm/W. The tungsten filament bulb was widely adopted and remained in operation until recent years. Iterations and incremental innovation pushed its energy efficiency to new frontiers, ultimately producing more than 14 lm/W by the 1990s.[13]

Rapid efficiency improvements in electric bulbs — combined with improvements in the electricity production and delivery systems — led to rapid declines in the cost of electric lighting. In the UK between 1900 and 1950, the average price of lighting services declined by 94 percent, from $414 per million lumen hours to $25 per million lumen hours. Between 1950 and 2000, the price decreased by another 85 percent. Lighting was becoming affordable to larger segments of the population and as a result, total consumption of electric light boomed. In the UK per capita lighting consumption from electricity jumped four orders of magnitude in 200 years, from 1,000 lumen-hours in 1800 to 13 million lumen-hours in 2000.[14]

As with subsequent transition periods in the history of lighting, more-efficient, cheaper light contributed to new opportunities for new products and applications, ultimately leading to fluorescent lamps and light-emitting diodes, two technologies that would open up even more uses for illumination and contribute to the growth of the industry.

Lighting

Fluorescent lamps generate light by chemical reactions that occur when electricity is applied to different gases inside a vacuum tube. The theory for the fluorescent lamp was developed in the mid-nineteenth century, and the first mercury vapor lamp, an antecedent to the fluorescent lamp, was patented in 1901.[16] But this early lamp emitted a bluish-green light and so was not appealing for residential use. In the 1920s, a German trio led by Edmund Germer piloted fluorescent light as we know it today, inventing a high-pressure mercury vapor lamp that increased the efficiency and safety of lighting.[17] In 1938, General Electric bought the patent from German inventors for $180,000, and commercial distribution of the first compact fluorescent light (CFL) bulbs began in 1938.[16] Circular and U-shaped lamps eventually gave way to spiral-shaped CFLs, which were invented in the 1970s and mass-produced in the 1990s.[17]

Early spiral CFLs produced 68.3 lm/W and were five times more energy efficient than the best tungsten filament bulbs.[13] Modern CFLs are up to four times more efficient than modern incandescent bulbs. Largely as a result of these energy efficiency characteristics, CFLs are much cheaper over their lifetimes than their incandescent counterparts. Lower costs are desirable and have led to the widespread uptake of CFLs around the globe.

Light emitting diodes (LEDs) run electrical current through a small electrical component (called a diode) to create light. The first LEDs were very expensive until they became mass-produced by the Monsanto Company in 1968.[18] The efficiency of LEDs has increased dramatically, while costs have declined. The illumination output per LED has increased by a factor of 20 every decade since the late 1960s, while the cost per lumen has fallen by a factor of 10 every decade.[19] As a result the technology has become pervasive, occupying new illumination niches because of its long life — up to 50,000 hours compared to the 10,000-hour lifetime of a CFL — and its ability to emit bright light from a very small volume.[20]

CONCLUSION

In the past three centuries, the energy efficiency of illumination has increased by a factor of about 650, from 0.076 lm/W (tallow candles) to 68 lm/W (incandescent lights and CFLs).[13] Meanwhile the cost has plummeted from $24,600 per million lumen-hours in 1700 to less than $5 per million lumen-hours today.[14] Cost declines and performance improvements created opportunities for new products, applications, and whole new industries, from candles to town gas, kerosene, and electrification. From 1800 to 2000, the price of lighting services in the UK decreased by over a factor of 3,000,[12] the energy efficiency of lighting improved by a factor of about 1,000,[14] the total consumption of lighting services increased by over a factor of 43,000, and the energy used for lighting increased by a factor of 100.[12] The history of lighting shows that efficiency improvements and their associated cost declines are part of a synergistic process of innovation that opens up new ways of using light, makes light more available to larger segments of society, and contributes to an overall increase in lighting-related energy use.

In the future, the global use of lighting may saturate, just as it already has in the residential, commercial, and even the industrial sectors of some developed economies. But many of the homes, offices, and factories in underdeveloped and industrializing economies still rely on relatively inefficient incandescent lighting for a relatively limited number of purposes. As newer, cheaper, and more-efficient lighting technologies are introduced in these contexts, the number of uses for lighting, and per capita lighting use, will grow. As economists Roger Fouquet and Peter Pearson conclude in a recent analysis that considers historical lighting energy consumption in the United Kingdom, "The combination of rising incomes and access to much more efficient lighting technologies [in developing countries] could imply that the consumption of lighting would grow very rapidly." The authors continue: "This could be accelerated in those countries, such as China and India, in which the major rise in income and the dramatic fall in lighting prices get compressed into a few decades, rather than the two centuries required in the United Kingdom."[12] In these industrializing contexts, energy efficiency-related improvements in lighting are more likely to lead to a net increase in energy consumption.

A CASE STUDY IN ELECTRICITY PRODUCTION

Photo Credit: Shutterstock

In places such as India, the potential for rebound effects may be high. Today, about 75 percent of India's population has access to electricity, but demand is far outpacing supply in meeting the growing electricity needs of the country. Electricity shortages have resulted in loss of profits and productivity for many companies, as plants and business have been forced to shut down or slow down manufacturing.[21]

The electric power production and delivery sectors — generation, transmission, and distribution — of industrializing economies such as China and India have benefitted from generous international funding for energy efficiency improvements. Both governments[22] and Western-based philanthropies, hoping to reduce energy consumption and greenhouse gas emissions, see electric power production and delivery systems as a prime target for efficiency improvements.[23] However, while energy efficiency efforts in the electric power production and delivery sectors should be commended for contributing to the improvement of livelihoods and access to electricity, they are unlikely to lead to large absolute reductions in energy consumption. On the contrary, increases in the efficiency of the electric power production and delivery in China, India, and other places with large unmet electricity demands are likely to lower costs, accelerate energy access, and open up many new ways to use electricity. Taken together, these processes may lead to an overall increase in electricity consumption.

This assertion is supported by the findings of economists and analysts who have studied the relationship between efficiency improvements in the electric power production sectors in different countries and across different time periods.[5,24, 25] Jeffrey Dahmus and Timothy Gutowski of MIT's Laboratory for Manufacturing and Productivity, who study historical trends in efficiency improvements and consumption in the United States, find that while the efficiency of electricity production from coal, oil, and natural gas has increased by about 1.5 percent per year (on average), the growth rate of the consumption of these fuels for electricity production has been more than quadruple the rate of efficiency improvements. Although rising incomes, population growth, and other factors also drove this increase in electricity consumption, Dahmus and Gutowski conclude that efficiency improvements in electricity production may have led to an increase in energy consumption, or backfire.[24]

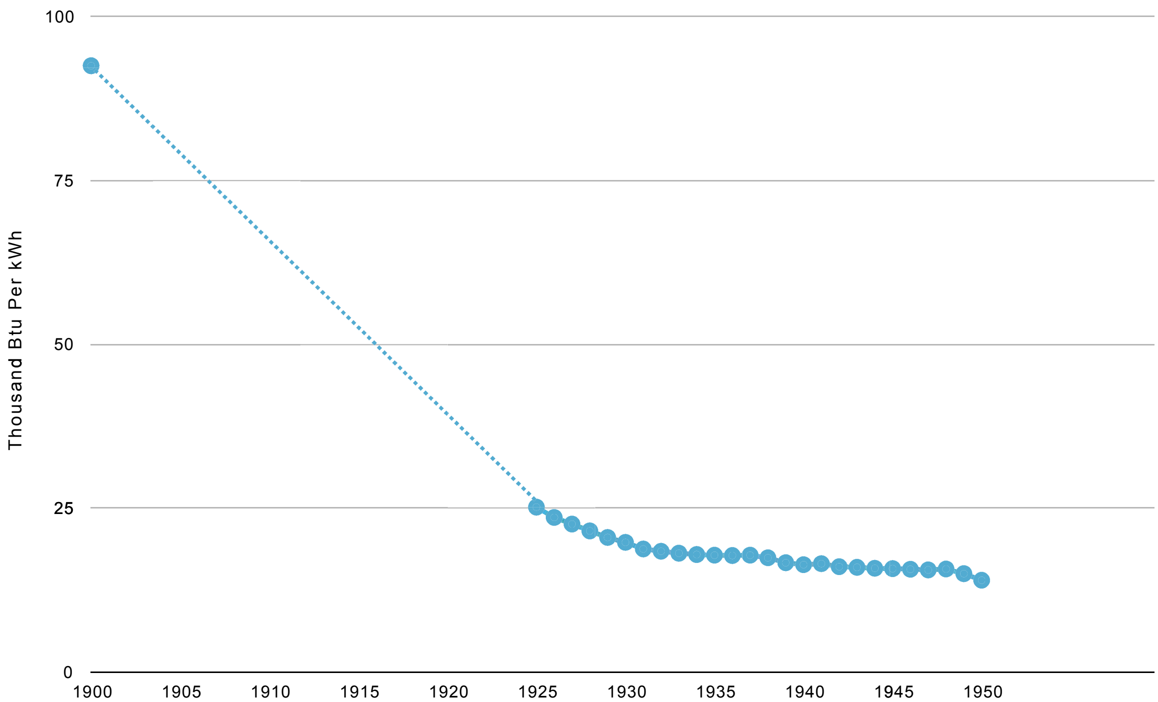
The evidence for backfire in the electricity production and delivery sectors is especially strong in industrializing economies such as early twentieth-century America, or modern-day China and India, where demand for electricity services is far from saturated.[26] In such cases, energy efficiency improvements alleviate monetary resources that are quickly reallocated for further electricity production to meet growing demand. And by lowering the cost of electricity, energy efficiency improvements in the electricity production and delivery sectors enable new uses of electricity that were once too costly, including appliances, electronics, and other modern services. There is no better example of these processes than during the period of electrification of the United States from 1900 to about 1950.

FROM EDISON TO EISENHOWER: HOW EFFICIENCY IMPROVEMENTS HELPED ELECTRIFY AMERICA

Thomas Edison introduced the first commercial electric power system in New York City in 1882. Efficient for its time, Edison's Pearl Street electric generating station used one-third of the fuel compared to its predecessors — about 138,000 British thermal units of coal per kilowatt-hour of electricity generated (Btu per kWh). The station delivered direct current (DC) electricity to 59 customers in the Wall Street area at a price of $5.5 per kWh (converted to 2012 USD).[27] By the end of the 1880s, several cities had similar small central stations that each served only a few city blocks. Electricity distribution range was severely limited because of energy loss in DC transmission lines. The innovation of a key technology, the transformer, greatly enhanced transmission efficiency and opened the industry to rapid development.

Electricity Production

Electricity Efficiency



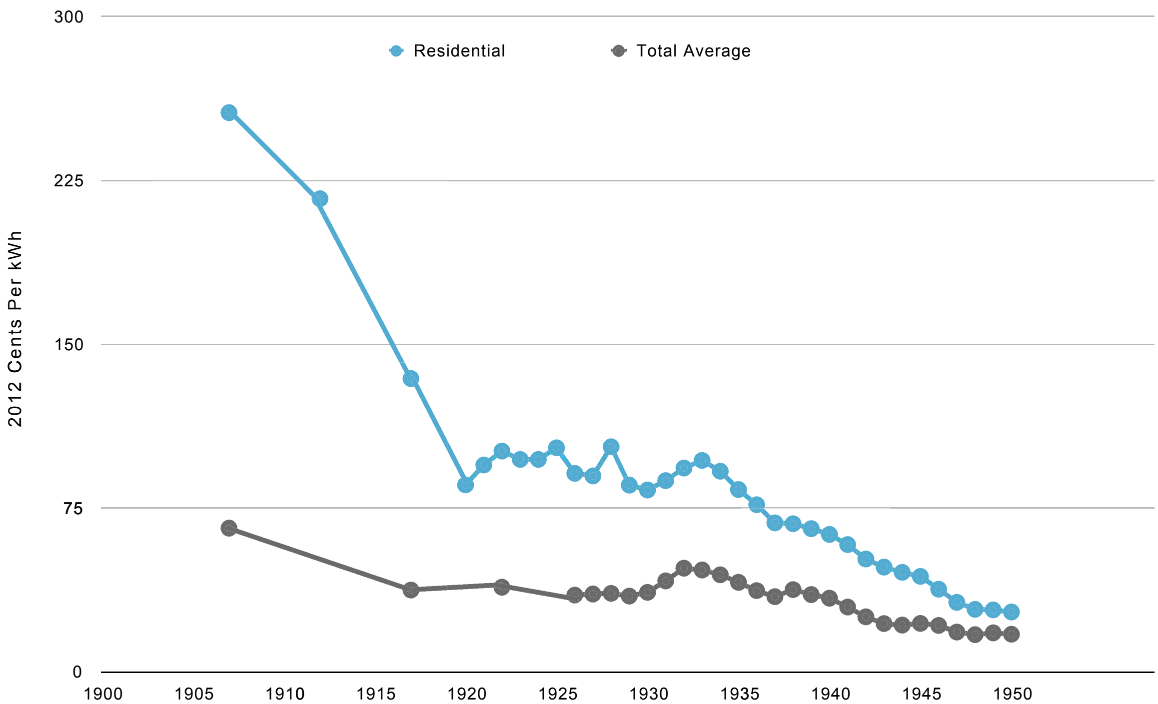
Source: United States Bureau of the Census (1975)

Between 1900 and 1950 the amount of energy fuel required to produce one unit of electricity to consumers in the United States declined by 85 percent.[28]

The first transformer was successfully demonstrated at scale in Germany in 1891. This innovation enabled use of relatively high-voltage transmission, capable of carrying alternating current (AC) power over long distances with relatively low energy losses. In 1896, George Westinghouse began the development of a hydroelectric project at Niagara Falls that transmitted significant power more than 20 miles away to Buffalo, New York. Westinghouse's Niagara Falls generation station set in motion the tradition of locating AC generators some distance from load centers, linking them by high-voltage transmission and using transformers to reduce the voltage for consumer end use.[27]

Electric utilities spread rapidly in the 1890s. Municipally owned utilities predominantly supplied street lighting and trolley services, while privately owned multiservice utilities supplied other residential, commercial, and industrial services, aggressively competing for central city markets.[27] Efficiency-related technological improvements contributed to a 12 percent reduction in the price of residential electricity by the turn of the century, to about $4.4 per kWh (converted to 2012 USD).[28]

Electricity Prices



Source: United States Bureau of the Census (1975)

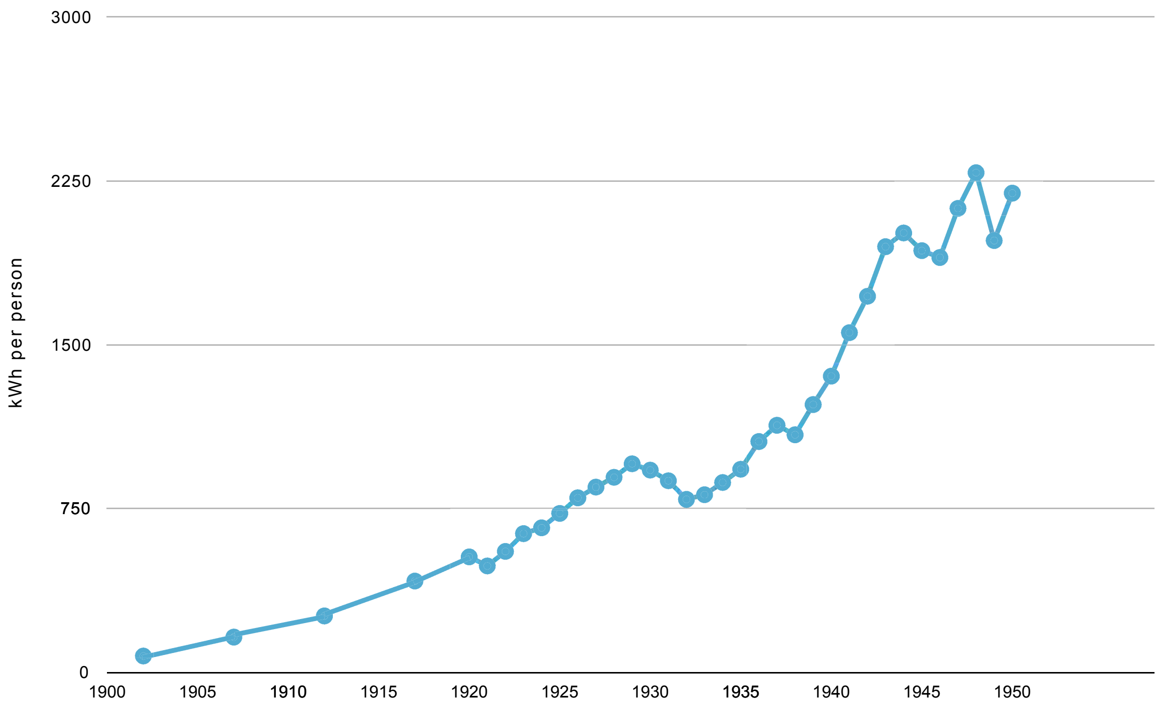
Energy efficiency improvements, driven by investment and innovation in more-efficient electricity production and delivery technologies, contributed to a dramatic decline in the price of electricity (other factors, including declining fuel prices, also contributed). Between 1907 and 1950, the average electricity price for all services declined by nearly 75 percent, while the price of residential electricity declined by about 95 percent.[28]

Growing economies of scale in the early 1900s meant that utilities could invest in the development of more-efficient technologies. Larger, more efficient steam turbine–powered generators quickly replaced older steam engines. Increasingly higher voltage power lines greatly reduced transmission heat loss. Alternating current power lines with voltages up to 150 kilovolts (kV) were in place by 1910, and by 1922, the first 245 kV line had been commissioned. Between 1902 and 1925, the heat rate of electricity production (the amount of energy used by the electric power sector to produce and deliver one kilowatt-hour of electricity to consumers) in the United States declined from 92,500 Btu per kWh to 25,000

Electricity Production

Btu per kWh,[27,28] a staggering 73 percent energy efficiency improvement. By 1935 the heat rate had declined another 30 percent to 17,850 Btu per kWh.

Per Capita Electricity Production



Source: Bureau of the Census (1975); Maddison (2010)

The declining cost of electricity drove demand for electricity. Between 1900 and 1950, per capita electricity production increased by a factor of about 30.

Energy efficiency in the sector contributed to a fivefold decline in the price of residential electricity between 1902 and 1929, from $4.4 per kWh to 86 cents per kWh, and these efficiency-related cost declines contributed to rising demand for electricity too. In 1907 only 8 percent of all residential dwellings were using electricity; by 1930 this figure had grown to 68 percent. Between 1902 and 1929 the country's per capita electric power output grew thirteen-fold from 75 kWh per person to 950 kWh per person.[28]

The pre-World War II years saw electricity generation systems continue to grow in size and efficiency. Maximum turbine sizes and pressures doubled, and steam temperatures increased. Generator cooling by pressurized hydrogen was introduced, resulting in higher generator outputs. By 1939 the average heat rate had dropped to 16,700 Btu per kWh. Improvements

Electricity Production

in transformers, circuit breakers, protection and reclosing devices, and transmission and distribution systems also continued, increasing the efficiency and reliability of electric utility systems.[34]

Efficiency improvements and an increasing share of federally backed hydroelectric power continued to drive down the cost of electricity, which fell to 63 cents per kWh by 1940.[27] Meanwhile, electricity production through the 1930s grew at a compound annual rate of 4 percent. Per capita consumption reached 1,350 kWh per person, a nearly 50 percent increase from a decade earlier.[28]

During the World War II years, electricity generation grew at a high annual average rate of 7.5 percent,[27] reaching 1,930 kWh per person in 1945.[28] This growth was powered by large, low-cost, efficient electricity systems. Not all of the wartime electricity demand growth was to fuel the industrial war effort. Residential and commercial demand also grew rapidly, and by 1945 almost one-half of all farm dwellings were electrified. By 1945 the sector was consuming 15,800 Btu per kWh, down from 16,700 in 1939, and this contributed to a 2.3 percent compound annual decline in the cost of electricity in the war years.[28]

CONCLUSION

The electrification of the United States is analogous to today's electrification of China, India, and other industrializing regions. Just as energy efficiency-improving technologies played a crucial role in reducing the cost and enabling the expansion of electricity systems in the United States, the introduction of more energy-efficient technologies in China, India, and elsewhere is reducing the cost of electricity services and is opening such services to new industries and new demographics. Alongside rising incomes, urbanization, changes in consumer preferences, and other socioeconomic and demographic trends, energy efficiency improvements in these electricity systems are contributing to growth in the consumption of electricity.

A CASE STUDY IN IRON AND STEEL

Along with rising incomes and population growth, improvements in energy efficiency and associated cost declines contributed to rapid growth in China's steel production. China's powerful ascent in global steel production follows similar trends in Europe and the United States, where both incremental and stepwise efficiency improvements led to significant increases in steel output.

From the Middle Ages to nineteenth-century England to modern-day China, iron and steel production has been characterized by technological innovation that leads to improvements in the efficiency of fuel, machinery, and labor. These efficiency improvements have tended to reduce costs and create opportunities for innovation, frequently driving greater production and energy consumption. As we will see in the sections that follow, leading economists from William Stanley Jevons to Nathan Rosenberg and Harry Saunders have posited that the potential for energy efficiency backfire has been present in the iron and steel production sector throughout its history. Backfire in the sector is most likely in industrializing economies, where iron and steel demand is far from saturated. The intuition of these thinkers is supported by both theoretical and empirical evidence of backfire.

BACKFIRE IN EARLY IRON PRODUCTION

Cast iron, first used as early as the fifth century BCE in China, arrived in Europe in the Middle Ages and spurred the development of the blast furnace. The blast furnace enabled better extraction of iron from the iron ore and allowed the cast iron to be poured into molds directly at the base of the furnace, improving energy efficiency and opening up iron to a variety of new products and uses.[29]

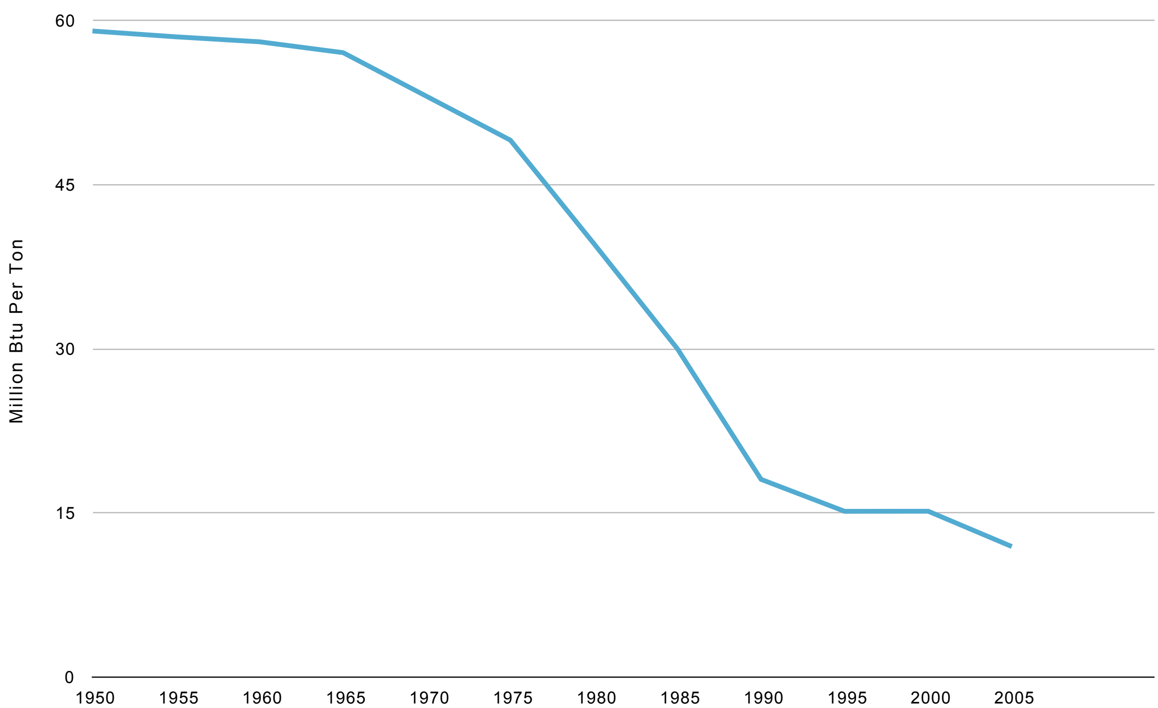
Iron and Steel

Innovation and efficiency improvements in a parallel technology — the steam engine — led to efficiency improvements in blast furnace steel production. Early steam engines invented by James Watt and others allowed them to be used in coal mines, facilitating greater production of lower-cost coal and opening steam engine technology to new applications. One new application of lower-cost steam engines was to pump air into blast furnaces, thereby increasing the blast temperatures, reducing the quantity of coal needed to make iron, and reducing the cost of iron.[30] Lower-cost iron, in turn, reduced the cost of steam engines, creating a positive feedback cycle. It also contributed to the development of railways, which lowered the cost of transporting coal and iron, thereby increasing demand for both.

As Jevons wrote in 1865, referring to backfire in the Scottish iron industry, "…the reduction of the consumption of coal, per ton of iron, to less than one third of its former amount, has been followed… by a tenfold increase in total consumption, not to speak of the indirect effect of cheap iron in accelerating other coal consuming branches of industry."[32]

BACKFIRE IN EUROPEAN AND US STEELMAKING

Steel Production Efficiency

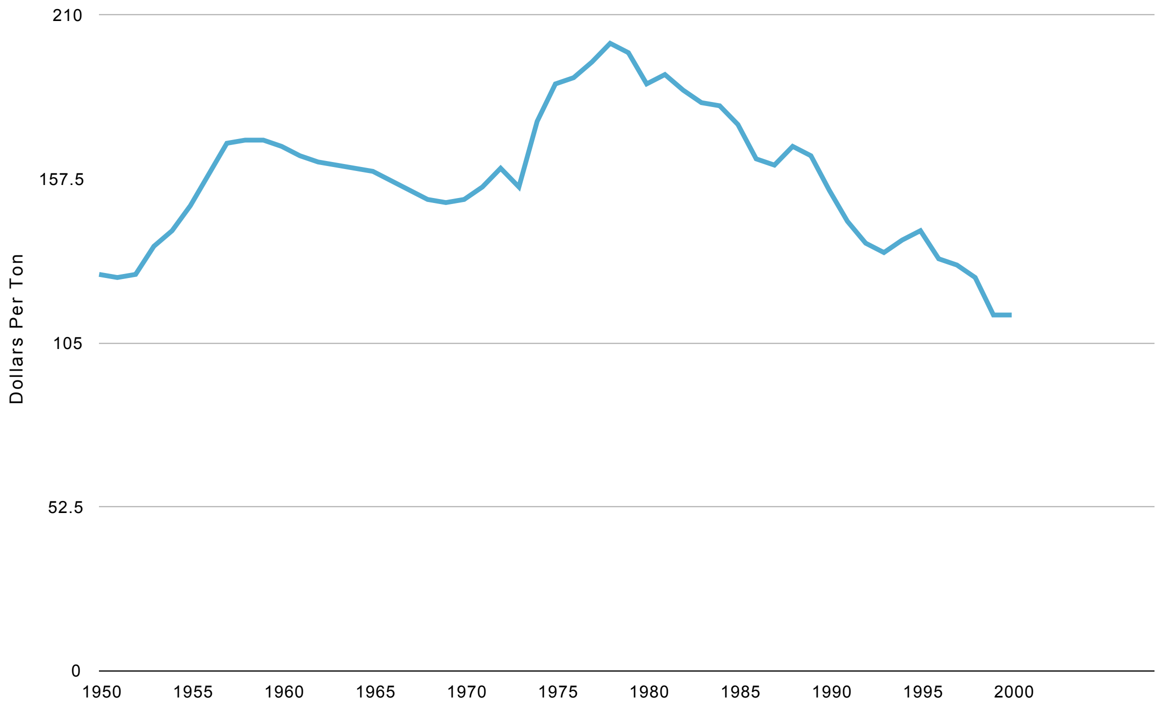


Source: United States Geological Survey (2013)

Between 1950 and 1975, largely due to the introduction of basic oxygen steelmaking, the amount of energy it took to produce a ton of steel in the United States decreased by 17 percent. And between 1975 and 2005, due to the introduction of the electric arc furnace, the required energy decreased by an additional 75 percent.[31]

Iron and Steel

Steel Price



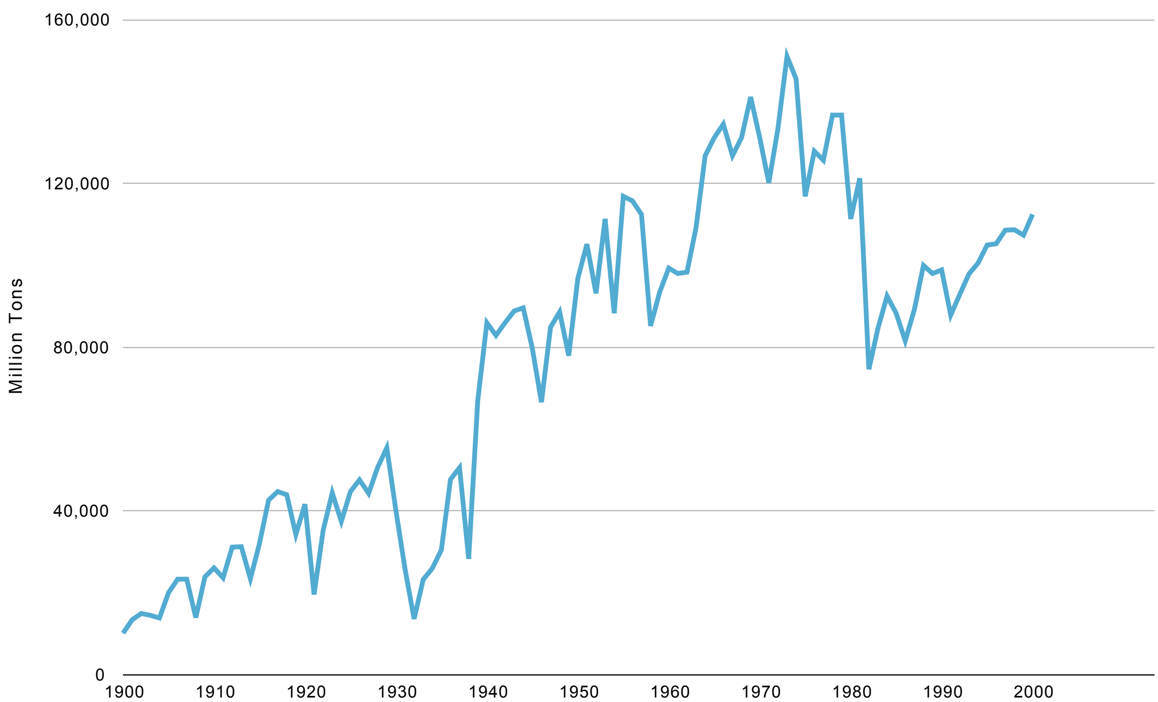
Source: United States Geological Survey (2013)

The rise of the electric arc furnace, and its associated energy efficiency and capital efficiency improvements, contributed to rising steel production. Between 1980 and 2000, partly as a result of efficiency improvements, the price of steel dropped by 40 percent.[31]

Modern steelmaking began in Europe in the seventeenth century as a very expensive, energy- and labor-intensive process. The earliest European steel was produced by coating wrought iron with powdered charcoal, heating it, and letting it sit to absorb carbon. After a few days of sitting, the iron bricks were separated and reheated to create "blister steel." Blister steel was reheated and beaten with a forge hammer to improve its quality. This energy-intensive, time-consuming, and costly process was not conducive to mass production.

The Bessemer process changed this. In 1856, British metallurgist Henry Bessemer invented an industrial technology that blasted pig iron with compressed air, creating an energy efficient way to produce high-quality steel in mass quantities and likely leading to significant backfire in steel production. As economist Nathan Rosenberg writes, "[The Bessemer process] was one of the most fuel-saving innovations in the history of metallurgy [but] made it possible to employ steel in a wide variety of uses that were not feasible before Bessemer, bringing with it large increases in demand. As a result, although the process sharply reduced fuel requirements per unit of output, its ultimate effect was to increase… the demand for fuel."[33]

US Steel Production



Source: United States Geological Survey (2013)

Lower steel prices opened new possibilities for its use and contributed to increased production and associated energy use.

The low-cost Bessemer steel initially found a large market in the production of steel rails, thereby facilitating the growth of the rail industry. In the mid-nineteenth century, the United States railway boom was underway, and iron was the dominant track material.[24] In 1867, 460,000 tons of wrought iron rails were produced, selling at $83 per ton. In the same year only 2,550 tons of Bessemer steel were produced, each ton selling at $170.[29] But efficiency improvements in the Bessemer process contributed to large cost reductions, and by the 1880s virtually all rail that was being produced was steel, which had become cheaper, easier to produce, and more durable. In 1884, 1.5 million tons of Bessemer steel rail were produced, each selling at $32 per ton. By the end of the century the cost per ton had dropped to $14, while the average lifetime and carrying capacity of rails had grown five-fold and eight-fold (compared to 1865), respectively.[29]

Iron and Steel

Due to its superior properties, Bessemer steel eventually found much wider application than wrought iron ever could, becoming an integral part of basic construction, buildings, automobiles, and appliances.[30] Greater demand put pressure on the industry to increase the efficiency of production. Open-hearth furnace (OHF) technology complemented the Bessemer process, allowing higher temperatures within the blast furnace through a process called regenerative heating. Regenerative heating, developed by Sir Carl Wilhelm Siemens and French engineer Pierre-Émile Martin, was designed to conserve heat and reduce fuel use. The Siemens-Martin process permitted the melting and refining of large amounts of scrap steel, significantly decreasing costs of steel production.

Basic oxygen steelmaking (BOS) eventually superseded the Bessemer process and the open-hearth furnace. This innovation greatly reduced the labor and capital costs of steel plants and reduced the time it took to produce steel. By the 1960s, BOS had become the dominant production method in the US, and its growth contributed to increased demand for steel. Between 1950 and 1975, the energy intensity of US steel production decreased by 17 percent, decreasing the cost of production and, along with rising incomes and population growth, contributing to an increase in steel production and associated energy use (see graphs).[31]

The rising energy prices of the 1970s created substantial problems for steel production, a highly energy-intensive industry. For its survival, the industry sought new energy-saving technologies. It was highly successful, with energy consumption per ton of steel produced declining by about 75 percent since 1975 (see top graph).[31] A number of process improvements contributed to this success, but a key component of the fuel productivity gains was the aggressive introduction of modern electric arc furnaces (EAFs).[34] EAFs were essential for the development of "mini-mills," small efficient plants that today produce about half of US raw steel production. Among their advantages, EAFs allowed scrap steel to be recycled, bypassing the most energy-intensive step of the traditional process, the blast furnace. However, the blast furnace is one of the most capital-intensive steps as well. Therefore, this technology has increased the efficiency of capital as well as energy.

The rise of the EAF, and its associated energy efficiency and capital efficiency improvements, contributed to an increase in steel production and its associated energy use. Between 1980 and 2000, the price of steel dropped by 40 percent while production and associated energy use increased. Economist Harry Saunders finds that from 1981 to 1990, energy efficiency rebound in the iron and steel sector was 185 percent.[5]

BACKFIRE IN CHINESE STEELMAKING

Despite having produced some of the earliest iron and steel thousands of years ago, China was slow to adopt modern steel production methods. A small Chinese steel industry first developed in the 1940s during the Japanese occupation, but by 1949 there were only 19 small steel mills with an annual output of about 158,000 tons. By 1952, with a push from the Communist Party, China was producing 1.3 million tons of steel using rudimentary technology.[42] During China's infamous Great Leap Forward (1958–1961) under Mao Zedong's leadership, China's steel output increased further, from 5.9 million to 12.2 million tons, but the production was extremely inefficient. Steel production stagnated until the Cultural Revolution, during which steel output rose from 15.2 million tons (in 1966) to 20.5 million tons (in 1976).[35]

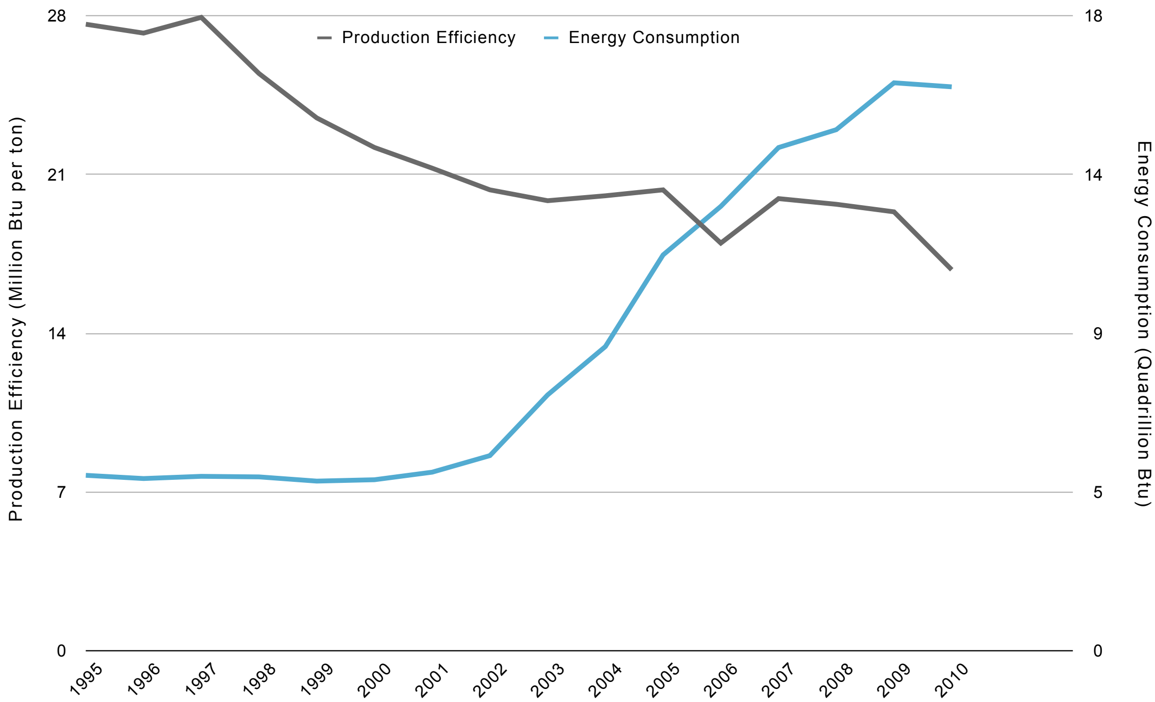
The opening and industrialization of the Chinese economy after 1977 led to the introduction of modern efficient steel production methods, including BOS steelmaking.[36] The Chinese steel industry's efforts to modernize included specific goals to decrease the energy intensity of the steelmaking sector, as well as increase the efficiency of other factors of production.

In the 1980s, the steel industry's focus was on improving energy conservation in the sector by introducing more efficient equipment, and in the 1990s, the focus shifted to implementing more energy-efficient production processes.[37] The results have been impressive, with the energy efficiency of the sector improving by 60 percent between 1994 and 2003.[38]

Along with rising incomes and population growth, improvements in energy efficiency and associated cost declines contributed to rapid growth in China's steel production. By 1996, China had surpassed all other countries as the world's leading steel producer, churning out 101 million tons, growing to over 626 million tons in 2010.[38] Since 1977, China's steel output has been growing at 14 percent every year, and total annual output has grown 26-fold. Increases in output have been accompanied by increases in energy consumption. In 2000, about 5 quadrillion British thermal units ("quads") were consumed for steel production, and by 2010 this had more than tripled to 16 quads.[39] While it may be tempting to entirely attribute the rise of China's steel industry to economic and population growth, econometric evidence indicates that energy productivity improvements also contributed to such growth.

Iron and Steel

Efficiency of Chinese Steel Production



Source: China Energy Databook (2013); Guo and Fu (2010)

China's modern steel industry is an example of how the introduction of more-efficient production technologies can contribute to the growth of an industry. Between 1990 and 2010, the energy efficiency of steel production in China improved by 40 percent with the introduction of modern technologies. Such improvements contributed to lower production costs, which, along with rising incomes and population growth, enabled the growth of the industry. Between 1995 and 2010, energy consumption in China's steel industry tripled.

CONCLUSION

As outlined in their twelfth five-year plan (2011–2015), China has ambitious plans for continued system-wide increases in steel production energy efficiency. Efficiency measures include forcing small companies into merger and acquisition agreements and relocating plants to coastal regions to reduce transportation material and energy costs.[40] Continued efficiency improvements in the steel sector will be extremely important as the country seeks to minimize costs while meeting the needs of growing urban populations. Buildings and infrastructure construction, which claimed 54 percent of China's steel output in 2008,[36] as well as vehicles and machinery, are growing rapidly in China to meet demand. India and other developing economies are following similar trajectories as they move toward the standards of modern industrial economies.

Iron and Steel

Energy efficiency in China's steel sector, as in other developing economies, will likely represent an important driver of industrial development. More-efficient steel production, however, should not be counted on to drive absolute reductions in energy consumption within the sector and could, in the long run, contribute to faster energy demand and emissions growth within the sector than would otherwise be the case.

CONCLUSION

Rebound mechanisms are part of a larger set of processes that contribute to the development and adoption of new technologies and whole new ways of using energy. In early electricity production and delivery in the United States, the introduction of the transformer greatly diminished energy loss in long distance transmission lines, enabling the expansion of electricity services beyond urban centers.

In the case of lighting, town gas and kerosene were superseded by the electric bulb, which eventually provided a more reliable and more energy efficient light than its predecessors. Energy efficiency improvements in electric lighting contributed to cost declines and its eventual use in virtually every major sector of the economy.

Likewise, in the early iron and steel industry, the invention of the energy-saving Bessemer process allowed the production of high-quality steel for myriad new industrial uses. In each case, energy efficient technologies were crucial enablers — alongside rising incomes, greater economic activity, population growth, better institutions, and better materials — of the vast expansion of services and energy consumption.

The implication for future global energy demand is significant. Rather than saving energy, in many cases we can expect the adoption of energy-efficiency-improving technologies to contribute to processes that lead to an overall increase in energy consumption.

The possibility, indeed the high likelihood, of backfire in certain sectors and in industrializing economies should caution us against heavy reliance upon energy efficiency as a climate mitigation strategy. In those parts of the world that will be responsible for the vast majority of future energy demand, demand for energy services in both end-use and production sectors of the economy is far from saturated. As energy-saving technologies reduce the cost of energy services, demand for those services will almost certainly rise, as they come within reach of populations that today can afford to consume little energy and as demand for new energy services rises with economic development.

Energy efficiency brings many social benefits, reducing the cost of energy services, contributing to the achievement of human development goals, and opening new frontiers for economic production and consumption. Emissions mitigation, however, is unlikely to be among those benefits. More energy-efficient technologies are likely to contribute to a planet that consumes much more energy than it does today. Higher energy consumption is a social good, strongly correlated with improved living standards, greater life expectancy, and many other important metrics of human well-being. Climate mitigation, however, will almost certainly require the almost complete decarbonization of the global energy supply, irrespective of what level of energy human societies consume.

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Please contact Alex Trembath (alex@thebreakthrough.org) with any questions or comments over data, sources, or methodology.

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