Historical Perspective on Energy Transitions – S. A. Van Vactor

> “Steam, water, wind - all had been harnessed for a little while and then abandoned. For centuries the energy of matter had run the world until it too had been superseded, and with each change the old machines were forgotten and new ones took their place. Very slowly, over thousands of years, the ideal of the perfect machine was approached – that ideal which had once been a dream, then a distant prospect, and at last reality: No machine may contain any moving parts.” Arthur C. Clarke, *The City and the Stars*, 1956

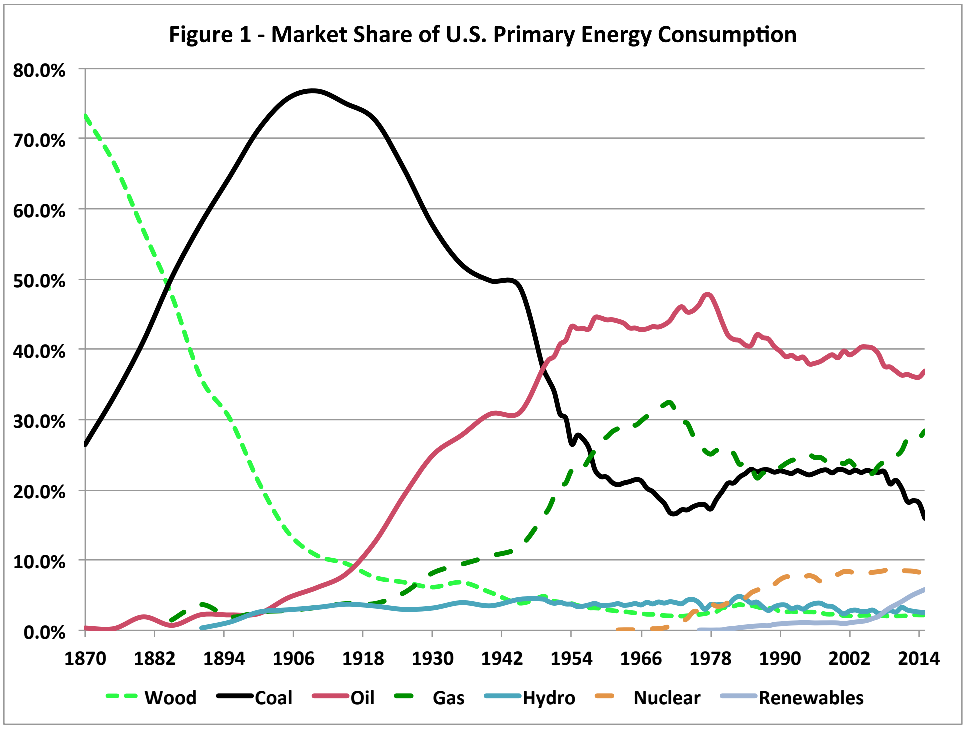
1. Major Energy Transitions

Mankind has relied on fossil fuels for a stunningly short time. Until the Industrial Revolution wood, wind, and water – renewables - were the primary energy resources. Home heating and cooking was done from a family hearth using mainly wood. If someone wanted to move about they walked, rode horses, or drove carts pulled by draft animals. Wind and water mills were used to grind grains and operate simple machinery but were not yet harnessed to industry. The first energy transition started when Great Britain began mining coal during the Elizabethan era, however it took several centuries before fossil fuels became a universal solution to the quest for heat, light, mechanical motion, and movement.

The second important energy transition followed the commercial discovery of crude oil in Pennsylvania in 1859. Oil has a number of superior qualities – high energy density, easy storage and mobility, and great flexibility of use. Demand growth was slow at first, but after the First World War it grew quickly, rapidly displacing coal and other sources in many industrialized countries until OPEC increased prices.

The third great transition began with the invention of the electric light bulb and construction of the Pearl Street power generation station in New York City in 1882. That transition turned night to day, with electricity becoming the most important energy form in modern life.

Figure 1 demonstrates the changing pattern of primary energy consumption in the U.S. For most of the 19th Century the U.S. was dependent on wood, but then coal began to replace wood, becoming the preferred choice for steam locomotives due its higher heat content. Thus, as the U.S. rail system expanded, coal consumption grew – by 1890 it was the dominant energy source. Oil had a very limited market, until Henry Ford and his contemporaries found a way to mass-produce automobiles. By 1920 lamp oil was largely replaced by electric lighting, and the industry shifted its attention to fueling motorized vehicles. Early in the 20th Century, the high cost of gasifying coal limited the market for "town gas." After World War II, however, high-pressure steel pipelines allowed natural gas to be moved from producing regions to population centers and gas demand grew rapidly. Hydroelectricity reached its limit in the U.S. about 1970. That and the oil price shocks of the 1970s prompted a nationwide program to build nuclear power stations. However, high cost and public protest stalled further development after 1985.



The oil price shocks also provoked interest in renewable power – solar and wind. These resources remained a small part of the overall picture for three decades, but are now growing rapidly. Since the transition from wood around 1890, the U.S. has been heavily dependent on fossil fuels for its energy supply. Such dependence peaked at 94% in 1970 and with a modest downward trend has fluctuated between 80% and 90% since then. In 2015 fossil fuels were 82% of total energy consumption. Finally, it is worth noting the changing dependence on imported energy. Dependence grew rapidly after 1970 as domestic oil and gas production declined. Despite countless energy policy initiatives dependence on imported oil grew, until the oil price rise from 2006 to 2008 stimulated the shale gas and oil revolution.

2. Energy and the Industrial Revolution

Mention "energy crisis" and most people think about OPEC and the oil shortages of the 1970s. However, the convulsions arising from those events pale in comparison to what

Great Britain faced in the Sixteenth and Seventeenth Centuries. At the time wood was the primary energy source. After recovering from the plagues of the 14th Century the British population grew rapidly and its once seemingly inexhaustible forests shrank at an alarming rate.[1] Similar resource exhaustions in previous eras had decimated economies and in some cases destroyed promising civilizations. The denuding of the prized cedar forests of Lebanon, the salinization of the Fertile Crescent, and the mysterious disappearance of Easter Island's inhabitants are thought to be examples of resource depletion, leading to a broader societal decline. Jared Diamond has referred to these and similar events as "ecological suicide."[2] However, such a collapse did not happen in Great Britain. Instead, something quite remarkable changed its society and went on to change the world.

The first and most important observation from previous energy transitions concerns the role of scarcity and price. Faced with rising prices of wood and charcoal, the British turned to an alternative - coal. Oil from surface seepages, coal and even natural gas had supplied other civilizations in the past, but the use was not systematic. Little or no effort was made to exploit these resources in an organized fashion by building up supply chains and a parallel consumer infrastructure. Things were different in Britain because growing intellectual interest in science and technological advance coincided with resource scarcity. In short, Great Britain had both an alternative resource and the means to exploit it.

At the time, the British were particularly willing to accept new ideas. The invention of the printing press in 1440 in Germany accelerated the movement of intellectual thought and information. In response, Europe's horizons expanded and academic institutions flourished. In England, Oxford University had been founded in the twelfth century and Cambridge followed a few years later. The Royal Society, which encouraged all types of scientific and advanced learning, was founded in 1660. In the decades leading up to the Industrial Revolution, open minds triggered *adaption* rather than *capitulation*, as had been the case in earlier times.

The switch from charcoal to coal required a vast array of adaptions, all stimulated by flourishing technological growth. John Nef pointed out that the switch required new smelting techniques and expanded the science of metallurgy, ultimately allowing new types of metal tools.[3] Likewise the increased demand for coal led to a series of inventions that turned out to be useful elsewhere, including the use of steam engines for pumping water out of flooding coal mines and railroads for moving ore. Table 1 illustrates some of the innovations and inventions that accompanied the coal industry's development and illustrates their linkage to the key inventions that propelled the Industrial Revolution.

The left side of Table 1 lists inventions in coal mining that ultimately helped foster the Industrial Revolution. The table illustrates the second important observation about energy transitions. Innovations aimed initially at developing new resources may migrate to other applications, where they in turn increase the demand for energy. Put another way, there is a feedback effect – a symbiotic relationship between the supply of and demand for the new energy source.

From today's point of view the Industrial Revolution is known as a period of great economic progress. Stepping all the way to back the Ancient World the average person did not fare too well. In the words of Thomas Hobbes: "the life of man, solitary, poor, nasty, brutish, and short".[4] Or, as Reverend Malthus prophesized, a golden age of good weather and good crops stimulated population growth and led directly to starvation and hard times when the tide reversed.

Table 1 - Innovations in Coal Supply and Demand

Coal Supply	**Energy Demand**
Coal replaced wood, as the price of wood and charcoal rose.	Growth in textiles, iron, & coal underpinned the Industrial Revolution.
Thomas Newcomen's 1712 steam engine invented for use in mining.	James Watt steam engine efficiency improvements, 1760s to 1770s.
	Richard Arkwright's Water Frame for spinning 1769 – water powered.
	Edmund Cartwright and Henry Cort in the 1790s developed the iron-framed Power Loom - steam from coal.
In 1758 the Middleton railroad carried coal to Leeds; in 1799 wooden rails were converted to iron edges.	1808 first steam locomotive. 1830 Liverpool, first steam rail passenger service.
UK Coal output: *1700, 3 million tons *1830, 30 million tons *1853, 72 million tons *1913, 292 million tons, 1 million employed *2014, 12 million tons, 14 thousand employed	By 1850: Kilometers of railway line installed: *Great Britain: 9,797 *Ireland: 865 *Germany: 5,856 *France: 2,915

No one kept macroeconomic statistics during the Industrial Revolution, but in recent times scholars have put together estimates of gross domestic product (GDP) and its annual growth rate.[5] Estimates do vary, but the latest research attempts to reconcile the various points of view and the data do present a consistent picture of events. As noted earlier, population doubled just before the British economy shifted from charcoal to coal. The period of population growth followed the Black Death pandemic that killed one-third of the population in 1349 and the "mini ice age," which began about 1300.

Table 2 summarizes population and economic growth estimates. The table reveals the third key observation about energy transitions – although the transition fostered new technologies and a better economy it did not happen immediately. In the case of Britain's Industrial Revolution, per capita economic growth was negligible until 1830, but then progressed at unprecedented speed from 1830 onwards. This is generally true about the impact of any new technology. The World Wide Web was created in 1990, but Google did not begin operations until 1998 and Facebook began in 2004. It took years for entrepreneurs to figure out how to put the new technology to commercial use and time for consumers to accept the new systems. It is also worth pointing out that GDP growth need not correspond to an increase in everyone's standard of living. There has always been some controversy about the benefits of the Industrial Revolution. In the long term it was clear that the standard of living rose dramatically, but in the initial stages many, including Karl Marx, claimed living and working conditions deteriorated.

Table 2 - Economic Growth Before and During the Industrial Revolution

Period	Population (million)	Real GDP £ 1700 Prices (million)	GDP £ Per Capita	Per Capita Annual GDP growth
England				
1270s	4.40	26.82	6.10	-0.02%
1300s	4.72	28.65	6.07	0.09%
1350s	2.65	20.80	7.85	0.54%
1400s	2.05	18.17	8.86	-0.06%
1450s	1.93	16.36	8.48	-0.07%
1500s	2.23	20.01	8.97	0.00%
1550s	3.12	25.76	8.26	0.17%
1600s	4.27	38.52	9.02	-0.04%
1650s	5.35	47.36	8.85	0.84%
1700s	5.20	65.93	12.68	
Great Britain				
1700	6.20	76.01	12.26	
1750s	7.43	102.90	13.85	
1800s	11.17	188.08	16.84	
1850s	21.69	526.98	24.30	
1870	25.84	765.13	29.61	
1700-1830				0.17%
1830-1870				1.16%
1700-1870				0.48%

Source: Broadberry, et al

Economists have yet to understand fully all the causes of economic growth. Some things are obvious – more people create more economic activity. Economic growth almost always accompanies population growth. There are, however, at least two other important aspects. The first is referred to as "capital deepening." Given a fixed number of laborers, output can be increased by adding the same type of capital. In a simple example, two woodcutters with two axes can produce more firewood than two woodcutters with one ax. In this example, there was no technological change, just the addition of another tool of the same type. But, what happens when you add a chain saw instead of an extra ax? In this case a new technology was added to the mix and output could be expected to zoom. If productivity, output per worker, does increase how do you measure the contribution of additional capital as compared to technological change? This is especially tricky when working with national statistics – capital investment is measured in sterling or dollars, but the mix of new and old technologies is largely unknown.

An estimate of the contribution of technological progress (and other less obvious changes) proceeds by calculating a residual. Formally this is known as "total factor productivity" or "TFP."[6] If, for example, inputs (the number of work hours and units of capital) are constant, but output increases 2%, the increase may be explained by changes in technology, regulations, climate, income distribution, and education levels.[7] These agents of economic growth are referred to as the "Solow residual." Quantitative studies conducted by him to estimate capital deepening found that it accounted for only 13% of observed economic growth.[8]

It is well established that the development of the coal industry was a driving force in Britain's economic development. But when Jevons expressed his apoplectic view of a crashing economy in *The Coal Question* John D. Rockefeller was 26 years old and only a few imagined that an even better energy resource was close at hand.

3. Impact of Oil

In the Eighteenth and Nineteenth Centuries whale oil was the principal fuel used for lamps. Growing demand and depleting whale stocks reduced the harvest, forcing whalers to sail further away and spend longer at sea. This in turn drove up costs, creating a desperate need for a replacement. As with Britain's wood crisis several centuries before, high prices of a depleting resource led to the search for an alternative. In order for kerosene to replace whale oil, however, there had to be new technologies to extract underground deposits of crude oil and to refine the raw product into a marketable commodity. In the 1850s rock oil was just as hard to come by as whale oil. It could only be recovered by scooping it from natural seepages or by digging pits. Surprisingly, it was the high value of salt that led to a cheaper recovery process. Salt, too, was scarce in the early 19th Century and necessary to preserve meat and other edibles. In 1808 the Ruffin Brothers developed drilling technology to exploit a salt marsh in upstate New York.[9] The idea was to extract brine from below the surface of the marsh to capture the salt. The project succeeded and the technology spread to other salt mines and for the recovery of fresh water. Thus, in 1859 when Colonel Drake went about exploring for "rock oil" in Titusville, Pennsylvania he could utilize a fledgling technology. His principal innovation was to use an iron pipe to line the drill hole, thus preserving the purity of the oil being extracted. His success set off an oil boom that quickly spread throughout Pennsylvania and other oil-rich states like Texas and Oklahoma.

In the decade before Colonel Drake drilled the first oil well a number of chemists worked with rock oil to order to extract lamp fuel. A Canadian, Abraham Gesner, coined the term "kerosene" and established a small market in the U.S. and Canada from 1850 to 1854.[10] In Europe, Ignacy Lukasiewicz improved the distillation process in 1852 and is generally credited with inventing the essentials of petroleum refining.[11] Once crude oil drilling developed and supplies grew, kerosene proved to be an acceptable replacement for whale oil, but it turned out that it was not the only use for the new energy source.[12]

Table 3 provides an overview of milestones in the supply and demand for oil. From the first major discovery in 1859 it took nearly a century for oil to overtake coal as the most important energy source in the U.S., despite an abundant domestic supply

Table 3 - Milestones in Oil Supply and Demand

Oil Supply	Oil Demand
1859 Colonel Drake's Pennsylvania oil well opens up new supplies of "rock oil."	1847 James Young distills lamp oil from natural oil seepage, 1850-54 Abraham Gesner develops "kerosene" market, 1852 Ignacy Lukasiewicz improves kerosene distillation.
1886 U.S. oil consumption reaches 1% of total energy consumption.	1886 Karl Benz receives first automobile patent.
1901 Spindletop discovered in Texas, Oil booms across North America	1900 Waste products from refining provide incentive for the internal combustion engine.
By 1910, oil discoveries in Persia, Sumatra, Mexico, et.	1911 to 1914 Winston Churchill converts Royal Navy to oil, nationalizes Anglo-Persian (BP) oil company.
1908 U.S. oil consumption tops 5% of total energy consumption, reaches 488 thousand barrels per day.	1908 Henry Ford Introduces the Model T.
1927 U.S. oil production reaches 22% of total energy consumption, 2.5 million barrels per day.	1927 Ford ends Model T production.
1950 U.S. oil production exceeds coal equivalent at 5.4 million barrels per day.	1950 U.S. automobile and truck production reaches 6.5 million units.

Simple distillation separates crude oil into three main parts – light ends similar to gasoline, middle distillates consisting of kerosene and diesel, and heavy fuel oils. Early refiners were after the prize – the middle distillates for making lamp oil. Disposing of the other two ends of the barrel, gasoline and heavy fuel oil, simply drove up refinery costs. Newspaper reports of the time depicted local refiners sneaking down at night and dumping gasoline into rivers.[13] Ultimately this proved unnecessary, as the ready availability of cheap gasoline provided an impetus to develop the internal combustion engine and the automobile. Most of the early engines could run on a variety of alcohol and petroleum fluids, but rapidly growing supplies of crude oil and gasoline derived from it locked the two developments together.

Karl Benz with, the help of his wife Bertha, is credited with inventing the first working automobile in 1886 powered by petroleum products similar to today's gasoline. The invention, however, stood on top of centuries of other inventions and innovations. Figure 2 is a picture of Karl Benz's first car, shaped largely like a big tricycle The Mercedes Benz website also provides a colorful account of the process of invention when Bertha took the car out for a spin:

> In the early hours of a fine August day in 1888, together with her sons Richard and Eugen, and without the knowledge of her husband, Bertha Benz took to the road with the Benz Patent Motor Car. She was undeterred by the fact that some stretches of the roads, which were normally used only by horses and carriages, were anything but suitable for the automobile. Lack of fuel, clogged valves or wiring chafed-through to breaking point – she found a solution to every difficulty on the journey. She resorted to a garter, a hat-pin, and plundered the ligroin stocks of pharmacies along the route. Even when the fuel ran out completely outside Wiesloch, and the Motor Car had to be pushed for several kilometres, she was not too proud to get down herself and help.[14]

Figure 2

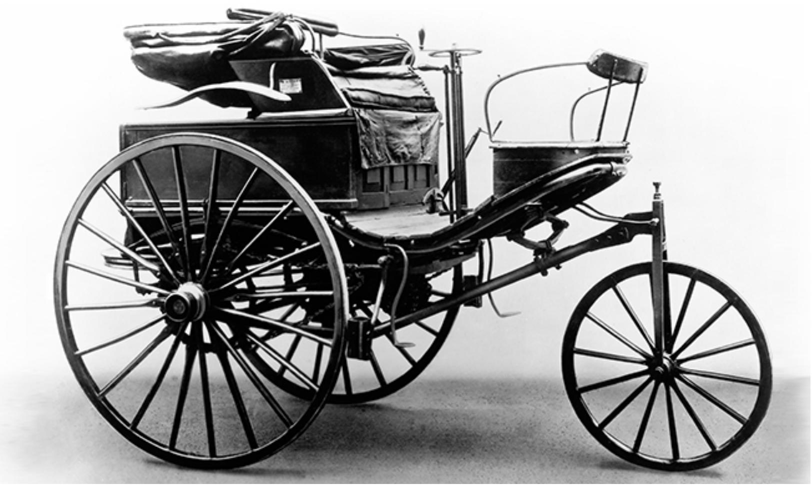
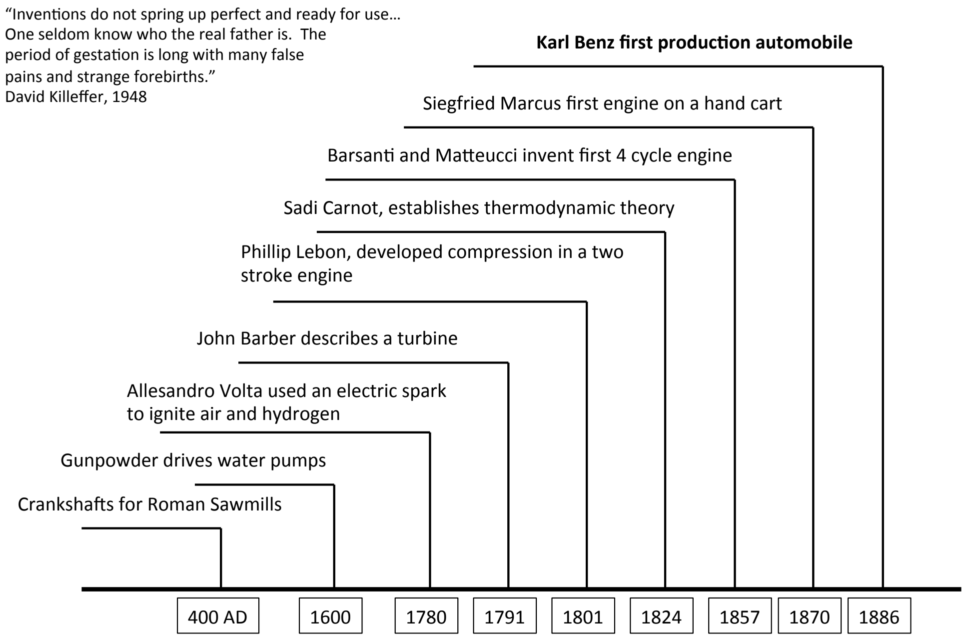


Figure 3 provides just a few of the important advancements that went into the first self-propelled vehicles. Even in 1886 a working automobile required a vast number of component parts – crankshafts, brakes, engines and sparkplugs, steering mechanisms, etc. It had taken centuries for the various components to be invented and developed so they could be combined in a motorized automobile. Needless to say, the first automobiles were handcrafted luxuries that only the rich could afford. At the beginning of the 20th Century, the Mercedes was on sale in the U.S. at a price of $12,450 and gasoline was around 7¢ per gallon.[15] Adjusting the sales price to today's dollars puts the Mercedes at $353,261, well beyond the range of almost everyone. In contrast, fuel for the car was downright cheap. The equivalent gasoline price in today's dollars was around $2 per gallon.

Figure 3 - Highlights of the Development of Automobiles



Henry Ford introduced the Model T in 1908 at a price of $950, but by 1923 the price had fallen to $269.[16] Ford, of course, had introduced his system of production lines and specialized labor. He also famously said that anyone working at Ford should be able to buy one his cars, and at a minimum wage rate of $5 per day his workers could. Within a few decades the Model T and cars built by Ford's competitors transformed the American transportation system and created a rising demand for petroleum products. Interestingly, the Model T could run on either gasoline or ethanol from corn or other grains. Ford did not entirely trust the oil industry and was uncertain as to how long supplies of crude oil would last.

There is another important feature of the automobile's early development. At the turn of the 20th Century it was unclear what form these vehicles would take – the internal combustion engine competed with electric and stream driven alternatives. According to Ford's recollection he had a key meeting with Thomas Edison in 1986 in which Edison explained: "Young man, that's the thing: you have it. Keep at it. Electric cars must keep near to power stations. The storage battery is too heavy. Steam cars won't do either for they have to have a boiler and a fire. Your car is self-contained – carries its own power plant – no fire, no boiler, and no steam. You have the thing. Keep at it."[17] It was not an accident that Benz and Ford succeeded; given the surplus of gasoline and the technology of the time, it was the superior choice.

The development of the internal combustion engine and the automobile illustrates the fourth important observation about energy transitions. Just as scarcity and high prices may drive the quest for alternatives, low prices may provoke entrepreneurs into finding a use for a surplus resource – in this case gasoline.

4. The Miracle of Electricity

Stuck on a desert island, Robinson Crusoe did his best to reinvent 18th Century Europe. "In the next place I was at a great loss for candles; so that as soon as ever it was dark, which was generally by seven o'clock, I was obliged to go to bed. I remembered the lump of beeswax with which I made candles in my African adventure, but I had none of that now. The only remedy I had was, that when I had killed a goat, I saved the tallow, and with a little dish of clay, which I baked in the sun (to which I added a wick of some oakum) I made me a lamp; and this gave me light, though not a clear steady light like a candle."[18] Robinson Crusoe was not only stranded on a distant island, he was stranded from what is now known as modern life. Living in the 18th Century he could not have imagined the electric light, which is now taken for granted in most of the developed world.

Those living before the invention of the electric light bulb spent much of their time in darkness or half-light. Candles or lamplight barely dented the gloom, yet still managed to dent the budget. The side effects could be nauseating – smoke and smells that turned a home into a stable. It had been know for centuries that electricity might be harnessed to produce light. Lightening, of course, lit up the sky in thunderstorms and by the mid-Century 19th Century, British inventors experimented with the arc lamp. More of less simultaneously in the U.S. and Britain a number of electric light bulb patents were granted. It took time to develop because early lights were expensive, power consuming, and short-lived. In 1879 Thomas Edison discovered that bamboo fibers could be used as a filament when enclosed in vacuum bulb. His patents paralleled those of William Sawyer and Albon Man in the U.S. and Joseph Swan in England. In the U.S. the two sets of patents were merged, allowing General Electric to be chartered.[19]

Electric light bulbs had little or no use, however, without a reliable power source. "It was exactly 3 p.m. on Sept. 4, 1882 when Thomas Alva Edison stood in the Wall Street offices of financial mogul J.P. Morgan and switched on his Edison incandescent light bulb – a bulb powered by a generator at his new Pearl Street Station power plant several city blocks away."[20] Initially the Station connected around 50 customers with 400 light bulbs, but by the end of the year 240 customers were supplied. Edison did not charge for the electricity for the first three months and when he did send out the bills customers found the cost comparable to gas lighting, despite the vastly superior quality.[21] The innovations and inventions at the Pearl Street generating station were as significant as the light bulb itself, because they put in place the complete package. "What makes Edison's contribution to electricity so extraordinary is that he didn't stop with improving the bulb -- he developed a whole suite of inventions that made the use of light bulbs practical."[22]

Table 4 lists key developments in the supply and demand for electricity.

Table 4 - The Miracle of Electricity

Electricity Supply	Electricity Demand
Electricity from chemical reactions.	Mid 19th Century - Increasing scarcity of whale oil; experiments with arc lamps and other forms of electricity.
1882 Edison generates electricity from coal in the Pearl Street station and supplies nearby businesses.	1879 Swan , Sawyer, Man, and Edison invent the electric light bulb. 1886 Spraque invents first practical DC electric motor for Trolleys.
Alternating current proves to be superior to direct current for transmission and many uses.	1896 Westinghouse and GE cross license AC motors, 100 HP achieved in 1897. 1902 First refrigeration and AC.
New Deal hydroelectric projects - Colorado River, Columbia River, and Tennessee Valley.	Creation of REA and federal marketing agencies.
First nuclear power plants: 1954 Obninsk Plant, Russia; 1956 Calder Hall, England; 1957 Shippingport, U.S.	
1961 first combined cycle power plant.	
2016 Renewable power generation capacity reaches 25% of total in California	2015 World power generation reaches 24 billion MWh.

It might have taken a century for the idea of coal-fired steam engines to migrate from mines to intercity rails, but it took only a few years for electricity to spread to other cities and expand its role. In 1887, five years after Edison's success in New York, Sebastian de Ferranti installed a similar generating station in London. Seven years after the opening of the Pearl Street Station, the Willamette Falls Electric Company (funded by General Electric) installed the first distance transmission line, stretching some fourteen miles, from the falls at Oregon City to Portland, Oregon. By then, the basic functionality of the electricity industry was in place – generation, transmission, and distribution. All that customers had to do was to flip the switch and pay the bill.

Once a full electricity system was in place its usefulness expanded dramatically: electric motors for manufacturing, pumps for sewerage systems, elevators that allowed cities to grow vertically instead of horizontally, traffic lights, motion pictures, aluminum smelting, and ultimately today's server farms. In the home electricity ended up powering appliances for cooking, cleaning, heating, air conditioning, and entertainment. Within a single generation – from 1890 to 1929 – the modern world sprang forth and reshaped ordinary lives.

The miracle of electricity illustrates the fifth important observation about energy transitions. Capturing a new energy source that provides unique products or services may penetrate markets quickly, even if it costs more.

5. Technology and Economic Growth

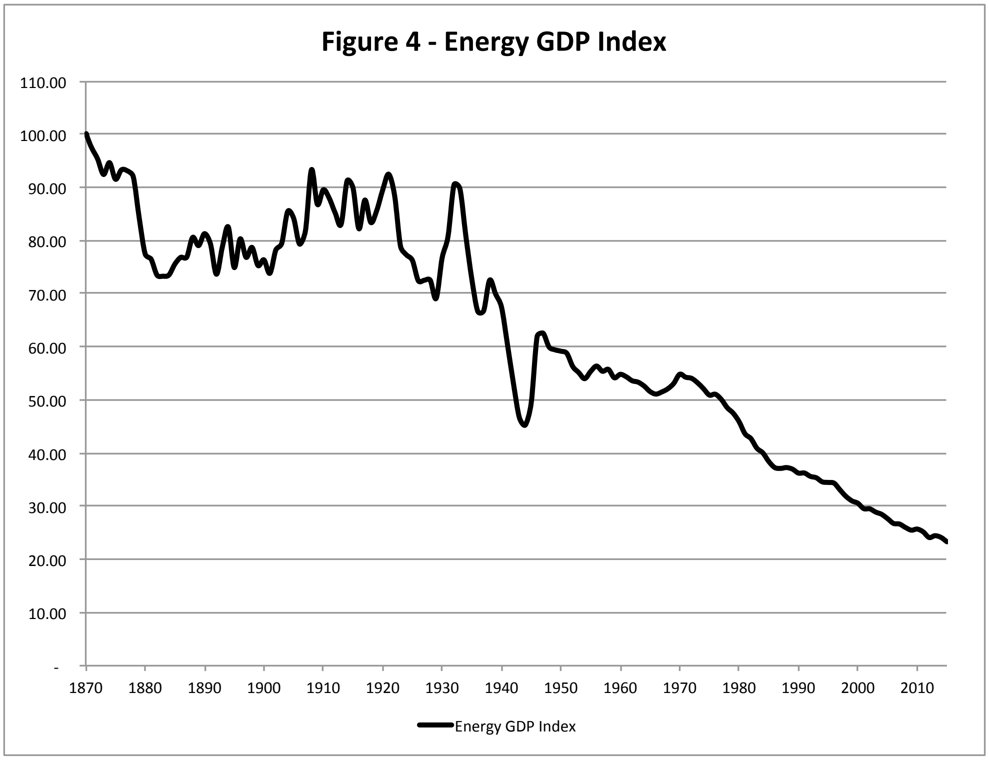
In his book, *The Rise and Fall of American Growth*, Robert Gordon argues that America's extraordinary century of economic growth that followed the Civil War was due to an onslaught of inventions and innovations that must be consider unique and are unlikely to reoccur. He makes a convincing case. When the various technological changes he itemizes are inspected, however, many of the key ones were dependent on the development of coal, oil, and particularly electricity.

Table 5 details many of the inventions and innovations made during this period and points out their relationship to fossil fuel development. In most cases the revolutions in home appliances and transportation correspond directly to the development and delivery of electricity and oil. Many of the other advances are only indirectly dependent.

Table 5 - Components of Economic Growth

Inventions and Innovations Identified by Robert Gordon	**Linkages to New Types of Energy Supplies**
The America Home: *Lighting *Fresh water and indoor plumbing *Refrigeration *Appliances *Central heating	Dependent on the availability of an electrical grid and fossil fuels for heating.
Transportation: *Intercity railroads *Street cars *Automobiles	Dependent on coal and later oil for railroads; street cars dependent on electricity or oil; automobiles dependent on oil.
Communications and Entertainment: *Telegraph and telephone *Postal service *Movies	Telegraph and telephone dependent on electricity in some form. Postal service dependent on various forms of transportation, mainly oil.
Health Care: *Improved life expectancy *Regulation of food and drug *Improved hospitals and physicians *Vaccines	Modestly dependent on electricity.
Working Conditions: *40 hour work week *Job safety	Minimum energy impact.
Insurance and Credit: *Mortgages *Consumer credit	Little or no direct impact of energy. Growth of the consumer society.
Manufacturing and farming: *Mechanization of Industry and Farming	Gordon covered the mechanization of industry and farming indirectly. Mechanization, driven by fuels and electricity freed up workers to move to service industries.

The impact of oil and electricity development on the U.S. economy in the early 20th Century was similar to the impact of coal in Great Britain in the 19th Century. In both cases the development of new energy resources helped spark major changes in industrial activity. These impacts can be traced by compiling historical data. For example, the relationship between energy use and GDP can be measured by calculating an index of energy divided by GDP and observing how the ratio changes over time. Figure 4 describes the index's movements from 1870 through 2015.



In the long run energy use per unit of GDP has declined, remarkably so. Starting at 100 in 1870, the index declined to 23 in 2015. Put another way, in 2015 Americans were able to produce more than four times the amount of products and services for the same level of energy input as in 1870. Of course a lot more energy is used today in contrast to 1870, but the economy's comparable output is proportionally much higher; in other words, energy efficiency gains have been extraordinary.

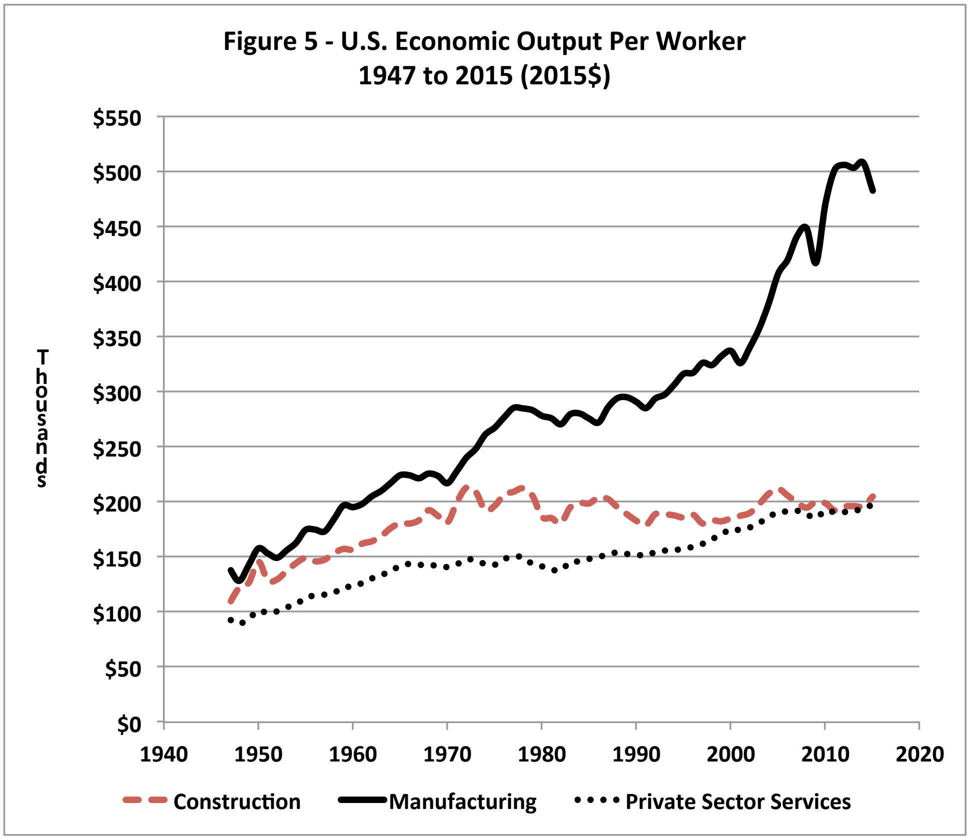
The data also suggest a series of interesting short run trends. From 1870 to 1880 the index declined from 100 to 77. Then, the index trended up, reaching 92 in 1921. This was also the period of major innovations in manufacturing. American industries applied new energy sources from coal, oil, and electricity to produce goods on a massive scale. As the American economy boomed in the decade of the Roaring Twenties, energy use per unit of economic output declined. The trend reversed after 1929, following the stock market crash and plunging economic output. By 1932 the index had risen back to its 1921 level.

World War II reversed the impact of the Great Depression and caused a drop in the energy-GDP ratio to 45 by 1944. The index popped back up to 63 in 1947 and since then has systematically declined to its present level of 23.

The agriculture sector has been one of the greatest beneficiaries of technological advances and it illustrates the astonishing impact of harnessing fossil fuels. In 1870 46% of the U.S. population were farmers or farm laborers. In the early 21st Century the figure has declined to 1.1% and, yet, agriculture output in the U.S. is much higher.[23] This is because farms have become mechanized beyond anyone's imagination. A century ago farmers still pulled wagons and combines with mules or horses and employed a corps of farm hands for the harvest. It is worth noting that before farm mechanization, about one-third of farmland had to be devoted to feed and pasture for draft animals.[24] Today, a farmer sits in an air-conditioned cab and harvests grains faster and more efficiently than ever before, all done with a barrel of diesel fuel, likely resting next to the barn, instead of in it. More formally, with respect to factor inputs; labor has been reduced, with capital equipment and fossil fuels added. All of this has been made possible by a continuing string of technological improvements and petroleum products.

There has been a similar trend in manufacturing. Recall the foundation of the Industrial Revolution – power looms replaced home spinning. Mechanization made it possible to increase output per worker employed. Initially, falling water drove industrial-scale looms. However, a limited number of suitable sites shifted weaving companies to the use of coal-fired steam engines. Once again, fossil fuels made it possible to substitute capital for labor. The efficiency of manufacturing continues to improve, although the nature of mechanization has changed. Energy is still needed for conveyor belts, production lines, motors, etc., but the substitution of robotics and computer controls for labor do not necessarily require greater amounts of energy; in some case energy use may actually decline.

Figure 5 illustrates the trend in workers per unit of economic output for three key sectors of the U.S. economy. Since 1947 output per worker has increased 251% in manufacturing, while private services output per worker increased by only 115%, about half that of factory workers. Interestingly, however, construction productivity increased by only 85%, less of a gain than in the service sector. This suggests that manufacturing and services have been able to utilize the revolution in computers and related information systems more effectively than construction. Nonetheless, In the U.S. the relative size of the manufacturing sector has shrunk from 39% to 19%, while private services have grown from 39% to 63%. This change reflects in part the migration of manufacturing jobs to overseas plants that have cheaper labor. It is also worth noting that the drop in manufacturing labor productivity from 2013 to 2105 may be due in part to the drop in oil prices, which stalled the boom in oil shale development. The loss of around $200 billion in annual revenue has driven down investments and expenditures to support the industry, figures which are included in manufacturing data.



Professor Gordon goes on to explain that many of the technological advances improved the standard of living without necessarily increasing per-capita GDP. Vaccines, for example, have greatly reduced disease and premature death, without substantially increasing traditional measures of economic output. Certainly improved healthcare, environmental cleanup, better working conditions, modern retailing, etc. have greatly enhanced average life styles in ways that are difficult to measure.

The energy sector has also made contributions to the standard of living that may not be recognized in the tedious calculation of the economic output of goods and services. A major thrust of Franklin D. Roosevelt's New Deal, was to bring electricity to rural areas that private companies chose not to serve due to the high cost. Roosevelt created the Rural Electric Authority (REA) and through the Army Corps of Engineers constructed large federal dams in the Colorado Basin, Tennessee Valley, and the Columbia River drainage. By the 1950s rural areas had been electrified. At that time the Bonneville Power Administration (the marketing arm for federal power in the Pacific Northwest) conducted a survey and asked rural residents about the electrification experience. The survey reported that the single biggest benefit of electric power was not lighting – it came in second. The greatest benefit was water pumping. Rural residents reported that electricity saved large amounts of time and human effort that had been expended just to pump well water. Today, it is difficult to understand how much of a revolution electricity made for ordinary lives.

Returning to Figure 4 it is worth exploring why there was a rising trend in energy per unit of economic output in the four decades from 1880 to 1920. During that period coal was never less than 72% of total energy consumption and demand grew at an annual compound rate of 33%. The "Iron Horse" was a belching, noisy machine. Coal was fed into the burner producing steam, which created thrust on large pistons and ultimately drove the train forward in a great rush of steam and smoke. It was a crude system with all sorts of moving parts and it often gobbled up much more energy that it actually delivered. In this time period, scientists and the general public could observe the direct relationship between energy use and work accomplished. Coal was used for everything from home heating to locomotives. Later on oil, natural gas, and electricity displaced coal in all but large stationary uses (primarily power generation). This is mainly because coal is bulky and dirty, has a lower energy content per ton, and has higher transportation and distribution costs. Even so, an infrastructure of production and use was in place while the other energy industries had to build something new from scratch.

With the exception of two anomalies – the Great Depression and World War II – there has been a steady improvement in energy efficiency since 1921. And, yet, most machines still have moving parts. Arthur C. Clarke's ideal of no moving parts may never be realized, but it is useful to think about the number of processes that began in the 19th Century utilizing significant mechanical motion and are now vastly streamlined.

This concept can be explained by an analogy. How much energy does it take to tell time? Since humans first became aware of their environment, the sun and moon have been used to mark time and the seasons. Over two millennia ago, time telling advanced with invention of a sundial. However, sundials had major disadvantages; they didn't work on cloudy days or at night. By Medieval times metalworking had progressed to the point that the mechanical clocks could be built. It made sense to place the clocks in high towers so that the face was visible throughout the village. The tower also provided the means to apply energy for the clock's movement. Initially, the clock hands were powered by using draft animal to lift large stones to the top of the tower. As the stones slowly wound down, the gears of the clock clicked forward moving the hands through the daily cycle. Whether by draft animals or electric motor, the energy to move a tower clock's hands is many orders of magnitude greater than that required to keep time on today's cell phone or battery powered wristwatch.

One reason for the large size of the medieval clock was precision. Europeans at the time did not have the metallurgy and casting capability to make miniature timepieces, since precision was affected by heat, humidity, and motion. As the technology improved, however, it led to indoor clocks, pocket watches and wristwatches. Timepieces got smaller and used much less energy. There are obvious parallels to this analogy in the development of computer systems and other aspects of modern life. The space race is said to have accelerated this development. In 1957, the Soviet Union launched an earth satellite – Sputnik, its beeping radio signal produced by vacuum tubes. The shock to Americans was profound, and the space race was on. However, the U.S. did not have the same heavy-duty rockets as the Soviets. The only way they could achieve the goal quickly was to reduce the payload's weight, and that led to miniaturization, including swapping the transistor for the vacuum tube. As transistors were reduced in size, energy input as compared to useful output was vastly reduced. As a historical footnote, the first commercial computer – UNIVAC had 5,200 vacuum tubes, its central memory could hold 1,000 words of 12 characters, and had a power draw of 120 kva or between 86 and 120 kw per hour of use.[25] To put that in perspective, it is around 200 times higher than the average hourly electricity usage of households in the U.K., most of which have far more powerful personal computers.

The data suggest that the reasons for productivity gains have varied through time. The large gains in the 18th, 19th and early 20th Centuries were due to enhancing mechanical motion by swapping fossil fuels for human and animal labor. This is why the depletion of Britain's coal resources and return to human and animal labor so alarmed Professor Jevons. The harnessing of fossil fuels was an extraordinary economic leap, with no real equivalent in history. Since then, however, the synergy between technological progress, energy use, and economic growth has changed. In today's world economic output increases in large measure due to efficiency gains – miniaturization, fewer moving parts, and computerization. In the future economic growth might be slower, as Professor Gordon suggests, but it could also be cleaner and safer, and it is from this perspective that a future energy transition should be viewed.

6. Visions of the future

Back in the Atoms for Peace era, energy analysts had a plan for the future. Fossil fuels would not last forever, but there were theoretical alternatives. Nuclear fission was the first step, to be followed by nuclear fusion. Those types of generators would likely be safer and have a lower environmental footprint. Analysts imagined a whole fleet of fusion reactors producing electricity and splitting water into hydrogen and oxygen. The hydrogen would then be piped to homes and factories, displacing fossil fuels. A future hydrogen economy is still on the drawing board for some, but the steps to get there are less certain. As stated by the U.S. Department of Energy: "The transition toward a so-called 'hydrogen economy' has already begun. We have a hydrocarbon economy, but we lack the know-how to produce hydrogen from hydrocarbons and water, and deliver it to consumers in a clean, affordable, safe, and convenient manner as an automotive fuel or for power generation."[26]

The earliest notion of a hydrogen economy may have been suggested by J.B.S. Haldane in 1923: "The country will be covered with rows of metallic windmills working electric motors which…will be used for the electrolytic decomposition of water into oxygen and hydrogen. These gasses will be liquefied, and stored in vast vacuum jacketed reservoirs."[27] Haldane's description utilizing windmills (as opposed to fusion generators) may be closer to today's reality, but the hydrogen economy remains a distant prospect. As Haldane pointed out the capital cost of such a system would be far greater than ones using fossil fuels – this was the prospect nearly a century ago and so far it is the same today.

In the 19th Century scientists could create light from electricity using an arc lamp or early light bulbs, but they had no idea of how to transform the emitting light into a commercial product. The hurdles were overwhelming. That was Thomas Edison's genius: His ability to envision a comprehensive system of production, distribution, and use while others simply created light in a laboratory. Although a hydrogen economy could use pipelines and wires it would require different designs. Moreover burning hydrogen emits only water, but when it is concentrated in the atmosphere it can act as a green house gas, with global warming potential. Is the world prepared for a "mist crisis?"

This leads to the sixth observation from previous energy transitions – developing a new energy resource, particularly a revolutionary one, may require a completely new delivery system. Even if a new system is not required, day-to-day energy policies must account for the impact on infrastructure. Expansions of pipelines or the electricity grid are crucial elements of energy planning.

There is always the possibility of future inventions that may totally change the present energy system. For example, gravity waves were recently detected and, in time, they will be better understood. If, for example, gravity could be amplified it would completely change transportation systems. To say the least, this is a remote possibility, but looking back to the 19th Century almost no one then could imagine the electric light. Likewise, it is all but impossible to grasp the state of scientific knowledge a century from now. As should be obvious, energy systems take decades to evolve and more often than not the main reason why past polices have led to unexpected consequences can be traced to a sudden technological change.

Electricity is not only the single most useful source of energy, it can be produced in a variety of well-established alternative technologies: solar, wind, hydro, nuclear, and fossil fuels. At the present state of knowledge an all-electric future seems more probable than the hydrogen economy. Given time, electricity has the ability to substitute for the direct use of petroleum and natural gas. For example, heat pumps and resistance heating can replace natural gas or oil furnaces for space heating. Likewise, electric motors and large-scale batteries can replace the internal combustion engine in cars and other vehicles. Over time the entire residential, commercial, and transportation sectors could be converted to electricity. Given today's technology, conversion of the agriculture and industrial sector would be more difficult, but even that might change as battery and other technologies improve. It is quite possible to imagine a future world in which electricity is the main or only form of energy consumed. Nonetheless, it is dangerous to assume that future energy commodities and infrastructure will mimic those used today; technological revolutions remain unpredictable.

7. The Natural Order of Energy Transitions

The mix of energy sources produced and consumed in the U.S. and the world has changed dramatically over recent centuries. In two cases transitions were sparked by scarcity and higher prices – wood to coal and whale oil to kerosene. In the transition to electricity, a superior form of energy triggered the change. The market gave entrepreneurs the incentive to develop new products and consumers the incentive to buy them. In all cases, the transitions followed the market's invisible hand, with limited government guidance. In retrospect, there was no reason to fear Jevons's warnings on coal shortages or Hubbert's analysis of peak oil, because new types of supply replaced old-style energy resources with remarkable ease. Everything went smoothly as long as markets provided the correct incentive.

In the 1970s there was considerable public concern about running out of oil. In contrast, most economists expected that scarce oil supplies and rising prices would prompt a market-driven shift to alternatives. In this environment energy policy could afford to be light-handed. Today, many in the scientific community believe climate change and global warming poses a major threat to the planet and the long-term welfare of its inhabitants. However, as long as fossil fuels are cheaper than alternatives, markets by themselves will not bring about a transition.

If the risk of global warming continues to rise and markets by themselves do not force a transition to alternative fuels, then energy policy must step into the breach. Emissions could be reduced by regulation or price adjustments, such as carbon taxes, etc. In either case, if such policies increase energy costs, the side benefits of improved living standards that accompanied previous energy transitions will be replaced by rising costs. Because there has been such a close relationship between the economy and energy use it matters whether or not energy policies are economically efficient. Inefficient policies could inhibit economic growth; efficient policies might enhance it or at least do no harm.

8. Implications for Phasing Out Fossil Fuels

It can be argued that fossil fuels were the primary motor of economic growth in the critical years that led to the modern world. There is a visible chain of causation for those that care to look. It starts with the switch from charcoal to coal. Coal mining created the need and the means to invent the steam engine and rail tracks. Steam engines went on to power looms and intercity rail transport. The growth of commercial trade provoked further geographic exploration and urbanization. Improved metallurgy and steam power using coal made wide scale oil drilling possible. Oil refining created low cost, energy-dense products that allowed self-propelled vehicles to replace the animal-driven wagons and carts. The electric light bulb superseded kerosene lamps and created demand for electricity and that new energy source, went on to power motors, pumps, furnaces, and a vast communications and entertainment complex. It is all but impossible to imagine modern life without these inventions nor to separate them from the economic growth that they helped to provoke.

Whether the focus is on energy security or climate change, those that craft energy policy need to recognize the complexity of the energy system. It is tempting to concentrate on one policy or technology as the "solution," but that is not how previous energy transitions advanced. In each phase of the transition, progress depended on a slew of seemingly unrelated inventions and innovations. Frequently whole new commercial systems and infrastructure had to be developed, requiring a host of individual actions. The transition did not follow from a top-down directive. Rather, the change was built from a wide variety of individual incentives many of which policy makers would have missed. In a market-based system those incentives are usually conveyed through the price mechanism.

Regulations have been used successfully to solve specific problems. For example, mandates made to car manufactures caused automobile exhaust pollutants to be reduced and over several decades that dramatically improved air quality. The policy worked because a specific cause and solution could be identified. Managing an energy transition, however, poses a much more complex problem. Changing one part of the system while ignoring other key parts could do more harm than good. Consider, for example, regulations mandating specific power generation alternatives, irrespective of cost. If such policies cause power prices to rise too much, then electricity demand will stagnate or decline and the transmission and distribution grid will not get expanded. High power prices, in turn, will shift consumption to fossil fuels for heating and other home uses. In short, the policy could easily enhance the use of fossil fuels instead of encouraging their phase out because it does not account for the system as a whole.

Economists stress the benefits of using the price mechanism to solve many problems of public policy, particularly the problem of externalities, which is how many energy issues are best understood. In the starkest terms, those that wish to exhaust carbon into the atmosphere risking climate change should pay for the privilege. As explained by William Nordhouse: "Governments must ensure that people pay the full costs of their emissions. Everyone, everywhere, and for the indefinite future must face prices that reflect the social costs of their activities."[28] Nordhouse notes that a price can be put on carbon either through carbon taxes or a cap-and-trade system. It should be added that the more universal the approach (the more energy commodities included in the taxing or pricing scheme), the more likely policy goals would be achieved. No one knows in advance what technology or combination of technologies will reduce climate change risk or how the energy system of resources and infrastructure needs to change. Piecemeal policies may do more harm than good.

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