Chapter 2
Energy and Food: The Megatrend of Megatrends

> If indeed the agricultural-sector proportions of poor countries were not declining, economic growth would indeed be hampered.[1]—Julian Simon (1996)

What Is Energy?

What is energy? There are many interpretations and perspectives from that of practical engineering design to philosophical abstraction. A wonderful place to start is with the late Nobel Laureate in Physics, Richard Feynman. In his 1961 lectures he discussed the concept of energy defined as an unchanging quantity: "It states that there is a certain quantity, which we call energy, that doesn't change in the manifold changes which nature undergoes. This is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens."[2] This idea is known as the first law of thermodynamics, or law of the conservation of energy, and *thermodynamics* is the study of the relationships among various forms of energy.

At its core, this energy concept is far from obvious. Why would there be a quantity that remains the same value before and after things change? We observe change all around us, the seasons, rain, aging. Yet the development of the concept of energy had to come by very careful observation of the world around us. We could have called this conserved "stuff" anything, but we call it *energy*. In defining energy via the first law of thermodynamics, we are not talking about "conserving" energy by running the heater less in your home during the winter, and we are not talking about burning less gasoline in your car. Energy is defined by a mathematical accounting principle stating that when you count all of the energy

[1]Simon [27, p. 600].

[2]http://www.feynmanlectures.caltech.edu/I_04.html.

C. W. King, *The Economic Superorganism*,
https://doi.org/10.1007/978-3-030-50295-9_2

residing somewhere at one time, and count it again at another time after something happens, you get the same total quantity.

To describe the concept of the conservation of energy, Feynman uses an analogy of a mother counting the number of her son's toy blocks. The mother knows her son has 28 toy blocks. Her son is a normal kid who is not very tidy, and he usually leaves the toy blocks on the floor of his room when done playing with them. He also sometimes takes his toy blocks into other rooms or places them in a toy box. When the mother comes to her son's room, often she cannot see all 28 blocks, but she knows there are 28 blocks in the house.[3] She is then forced to use clever ways of deducing where all of the blocks are located in the house. She weighs the toy box when she sees all 28 blocks (i.e., the box is empty), and she also determines that each block weighs a certain amount. She writes an equation for the conservation of blocks. On one side of the equals sign is 28 blocks. On the other side are two terms added together. The first term is the number of blocks she can see. The second term is a formula based upon the weight of the empty toy box and the weight of one block. Therefore, if she only sees 27 blocks, and if the box is too heavy by the weight of one block, she deduces that there is one block inside the box. If it is too heavy by the weight of two blocks, she knows there are two blocks in the box, and so on. One day the mother realizes that the (dirty) water level in the bathtub has increased, and she only sees 26 blocks with the toy box weight indicating it is empty. The two missing blocks are not in the box. The mother knows each block in the tub displaces the water in the tub by its volume, making the water level higher. She uses this information to develop another formula that tells her that the two missing blocks are in the bathtub.

Given these two examples, the mother has methods by which to count all of her son's toy blocks and determine where he has left them, even when she cannot directly see them. Feynman's analogy is that there are different forms of energy just like there are different places for the toy blocks to reside. In assuming that the number of toy blocks is always constant, when all toy blocks are not directly observable by sight, the mother must then come up with various ways to measure and test the location of any unaccounted blocks.

There is one critical difference between the conservation of blocks versus energy: we never directly see energy like the mother sees the toy blocks. Thus, to quantify energy in each of its different forms, we only use abstract mathematical formulas that are informed by measuring the world around us. More specifically our formulas quantify *changes* in energy. That is to say what we actually quantify is how much of each form of energy changed (e.g., increased or decreased) before and after some event. Imagine a ball resting on a table that is 1 m tall. We could say the ball has a gravitational potential energy equal to its mass times gravity times the 1 m if we consider a reference height as that of the floor. Alternatively, we could say the ball has zero potential energy at zero meters in height if we consider the reference height

[3]Feynman's story assumes that there is no way for the son to destroy any of the toy blocks or take them out of the house, such as by throwing them out of a window.

as that of the table. If the ball falls from the table to the floor, it will undoubtedly have fallen 1 m and the *change* in potential energy is equal to mass times gravity times the 1 m change in height regardless of whether we consider the table or the floor as our reference height.[4]

Energy is one example of a *conservation principle* that is a "…rule that some particular aspect of a phenomenon remains invariant or unaltered while the greater phenomenon undergoes certain specified transformations," Philip Mirowski writes in *More Heat than Light*, his deep history of how economics attempted to mimic the principle of energy [25].[5] As he states, because of the derivation of the concept of energy, "…did physics become the king of the sciences …" Mirowski credits René Descartes with the first concept of a mechanical physics with a conservation principle. Descartes was trying to describe the world as an "ether" of small particles transferring motion from one to the other. Today we call this idea the conservation of momentum. Think about a game of billiards. After the moving cue ball strikes a stationary ball, the previously stationary ball now proceeds in motion while the cue ball can stay at rest and the momentum and energy from the cue ball has been transferred to the other billiard ball. For a moving mass, its momentum is its mass times its absolute velocity.[6]

Gottfried Wilhelm Leibniz, through his concept that became the basis for calculus, discovered that Descartes was incorrect in the quantity that was conserved. Instead of mass times velocity, the conserved quantity is mass times velocity times velocity, or mass times velocity squared. Today, introductory physics courses teach that the kinetic energy of a moving mass is equal to one-half of mass times velocity squared.[7] Take again the billiards example. Not only does the cue ball move linearly (e.g., from one point on the table to another) but it is also rolling. Each billiard ball has two types of kinetic energy that describe its state: kinetic energy of linear motion and kinetic energy of rotational motion. Just like the mother must have more than one method of inferring the number of toy blocks of her son, there are at least these two types of kinetic energy for a billiard ball.

But in thinking of billiard balls, we avoid an important problem. Intuitively we surmise that nearly all of the kinetic energy in the cue ball can be transferred to the other billiard balls. Physically this 100% transfer of kinetic energy does not happen. To imagine why, think not of billiard balls bouncing into each other, but instead of a baker throwing a handful of bread dough onto the counter top. When he throws a spherical ball of dough onto the counter, it flattens into a disk without bouncing

---

[4]Recall from physics that gravitational potential energy is quantified as $= mgh$, where m is the mass of an object, g is acceleration of gravity, and h is the height of the object relative to some reference height, such as the floor.

[5]Mirowski [25, p. 13].

[6]Linear momentum is mass (m) times absolute velocity (v), or $m \times |v|$.

[7]Kinetic energy of a moving mass is $\frac{1}{2}mv^2$.

back up and the counter does not move.[8] There was kinetic energy in the dough when he threw it, but after it slams onto the counter, neither the counter nor the dough are moving. Both have no kinetic energy because both have zero velocity. The same concept happens with billiard balls, but a large percentage of the kinetic energy is transferred from one ball to another. The dough transfers practically no kinetic energy into the counter.

What happened to the kinetic energy of the dough? It turned into heat and *work*, but the early philosophers of science in the late eighteenth century did not know this. The "work" done is the flattening of the dough into a disk, and the rest of the kinetic energy converted into heat. However, if kinetic energy (for example) can be converted into heat and work (reshaping things), then perhaps heat can be converted into kinetic energy and work. The practical engineering pursuit of converting heat into kinetic energy and work played perhaps the most important role in advancing the scientific concept of energy.

In 1698 Thomas Savery invented his "engine to raise water by fire."[28] In 1769 James Watt (whose name is used as a unit of power) patented an improved base design for steam engines that powered the Industrial Revolution. In these new machines, a fuel such as wood or coal was burned to generate heat. This heat then boiled water into steam, and this steam injected into the machine could cause motion and physical work to be performed.

But just what do we mean when we say "work?" The first law of thermodynamics is often expressed as the change in energy of a system is equal to the amount of useless heat dissipated minus the work performed. Thus, a change in energy (e.g., from burning wood) can be translated into a combination of *heat* and *work*. Heat quantifies the amount of energy that did not turn into anything useful. Scientists refer to discarded heat as "dissipation." From a further practical perspective, I can expand the term of work to *useful work* which is performing activity in the real world that necessitates physical exertion.

It is this useful work that we can measure in the real world. Consider pre-industrial England and United Kingdom. Before the use of steam engines, humans (many of them children) and animals performed the duties needed to extract coal from underground mines and bring it to the surface [28]. Much of this "work" was to pump water from the mines as well as lift the coal (e.g., its mass) from underground. It is easy to imagine that pre-industrial coal mining would have been "hard work" and involve much sweating and physical exhaustion.

As these steam engines started to be used for pumping water to mine coal and performing other mechanical tasks, there remained an important question. Just exactly how did these "heat" machines function?

A major leap in knowledge came from Frenchman Sadi Carnot. He is credited as the founder of the science of thermodynamics. Carnot was primarily concerned with

[8] Technically the counter does move and vibrate a very small amount that is generally imperceptible without scientific instruments. For the purposes of the discussion here, it is useful to imagine the counter does not move at all.

conversion of heat into mechanical motion (kinetic energy). Sadi Carnot learned from his father, Lazare, who worked at the *grand écoles* of Napoleonic France that were tasked with investigating machines for military purposes. By thinking of the impact of such things as cannonballs and the "...physics of impact ...", Lazare translated his knowledge to the general idea of work.[9] He realized that a machine that was more efficient at performing work effectively minimized its internal "impact." A cannonball hitting a city wall is an extreme case of my example of the baker's dough hitting the counter. There is not enough kinetic energy in the dough to break the kitchen counter, but cannons were designed to do just that—transfer as much kinetic energy to a cannonball as possible such that it could release its kinetic energy into targeted structures and destroy them upon impact.

Carnot made the critical realization that the principle governing the function of steam engines "...was the result of the consumption or destruction of caloric [heat] from a warmer to a colder body, in direct analogy with the fall of water on a waterwheel from a higher to a lower elevation."[10] In effect, Carnot understood that for a heat engine to perform work, there had to be a transfer of heat from a high temperature source (e.g., the steam from burning wood or coal) to a low temperature sink (e.g., the ambient air or water).[11] If the temperatures are the same, then the efficiency of a heat engine to convert high temperature heat into useful work is zero because there must be a temperature *difference* to operate a heat engine. The low temperature is the reference condition for heat engines in the same way that earlier we had to think about a reference height in calculating the potential energy of the ball on a table.

This discussion of how much of a total change in energy from "before" to "after" some phenomenon becomes dissipated heat versus useful work brings us to the second law of thermodynamics. This law states that a practical device cannot take an energy input and convert all of it into useful work. Some of the energy must be ultimately converted to heat of no practical use. Using Carnot's insight into the maximum efficiency for a heat engine, we can describe how a heat engine cannot convert 100% of its input heat into useful work output. In the mid-1800s, armed with the ideas of the conservation of energy and efficiency of heat engines (not yet formalized into our current terminology or into the first and second laws of thermodynamics) scientists and engineers could perform experiments to characterize the "potential" energy from fuels (e.g., chemical energy from combustion) to perform work via machines.[12]

---

[9] Mirowski [25, p. 24].

[10] At the time the word "caloric" was used to describe a fluid that surrounded matter and was the cause of heat [25, p. 25].

[11] Carnot's famous expression quantifies the maximum theoretical efficiency for a heat engine to perform work based solely on the source (T_H) and sink (T_L) temperatures: efficiency $= 1 - \frac{T_L}{T_H}$.

[12] See Mirowski [25, pp. 35–66] for a discussion of the historical players that shaped the ideas leading to the formalization of the 1st and 2nd Laws of Thermodynamics.

Amazingly, both the engineering development of the steam engine and the concept of the second law of thermodynamics developed in ignorance of the relationship between the microscopic world of the air and water molecules in the steam and the macroscopic world in which we measure properties like temperature and pressure of the steam. It was only in the late 1800s, over half a century after Carnot's death, that Ludwig Boltzmann derived the idea that a gas, such as air, is made up of many tiny molecules banging into each other just like a continuous game of billiards. "Heat was just the combined kinetic energy of these tiny moving balls."[13] Hotter air is composed of faster moving molecules that have more kinetic energy. Since we cannot measure how fast each and every molecule is moving, Boltzmann described the statistical average of the molecules. Thus, Boltzmann's "statistical mechanical" description of gases provided a significant bridge for linking our micro to our macro descriptions of the physical world. As you will learn later in the book, physicists did not limit the application of statistical mechanics to physical phenomena. When they applied the concept to economic data, they found amazing similarity. But that will have to wait until Chap. 4.

Keep in mind that the second law of thermodynamics is not only about heat engines. First, from an engineering standpoint there are limits to converting inputs to useful work even in machines that are not based upon converting the heat energy of gases to directed mechanical motion. For example, the maximum efficiency of horizontal axis wind turbines, such as those we use to generate electricity today, have a maximum theoretical efficiency of 59% for converting kinetic energy in the wind to mechanical rotation of the turbine blades.[14] Individual solar photovoltaic (PV) cells have a maximum efficiency of 33.7% for converting sunlight into electricity.[15]

Secondly, the second law of thermodynamics also informs us how to interpret the economic process. For this statement, I quote perhaps the staunchest proponent for integrating thermodynamics and economics, Nicholas Georgescu-Roegen:

> Most important for the student of economics is the point that the Entropy Law is the taproot of economic scarcity. Were it not for this law, we could use the energy of a piece of coal over and over again, by transforming it into heat, the heat into work, and the work back into heat. [11]—Nicholas Georgescu-Roegen (1975)

The concept of energy is a great leap forward for science. With this one idea we can coherently compare the heat of moving molecules, the mass and speed of planets orbiting the sun, and a barrel of oil. If we perform our analysis right, we can design machines that take different forms of energy, as available within the environment, and convert them into useful work that replaces our physical labor, purifies materials, and transports us across the world or into space. Being able to perform thermodynamic work is one thing, but if you want to say how fast you want it done, you need to think about *power*.

---

[13] Sautoy [26, p. 89].

[14] This maximum efficiency is called the Betz Limit.

[15] The maximum efficiency of a PV cell is called the Shockley–Queisser limit, and it refers to the efficiency of a single p-n junction PV cell.

Power Is Not Energy

Now that we understand the concept of energy, we can understand *power*. It is important to understand power as related to, but distinct from, energy. Succinctly, *power describes how fast you are accumulating or consuming energy*. The simple way to remember the relationship between energy and power is to incorporate time. Power equals energy divided by the time it took to consume the energy, and energy equals power multiplied by the time during which power was consumed.[16]

Consider the following example to distinguish between energy and power. The amount of time for a NASCAR-style Toyota Camry race car to make a lap around the 2.5 mile Daytona race track is about 45 s while moving about 200 miles per hour (mph). Now imagine driving a normal Toyota Camry (one that you can buy at the dealer) around the Daytona NASCAR race track. You could reach a top speed near 100 mph, thus taking about 90 s to make a lap. Why does the race car make it around the track in shorter time? It has a more *powerful* engine. The NASCAR version of the CAMRY uses an engine rated at 700–800 horsepower, while the Camry that you and I can buy has a 300 horsepower engine. That is to say, to make it the same distance *in half the time*, the NASCAR Camry might consume about the same amount of fuel as the normal Camry, but in less time. To do that it needs a larger engine that can consume fuel at a higher rate. A higher rate of energy consumption is the same as more power.

At the scale of a country, if one country can consume energy in less time, then more work can be done each day, week, month, and year than another country that consumes its energy at a slower rate. This concept is immensely important in understanding how energy consumption, or more precisely power, relates to economic activity because economic activity is also measured as a *rate*. For example, gross domestic product (GDP) is expressed in units of money per year, not simply money. The phrase *energy consumption* implies a rate of use of energy, which is units of power. Thus, as we will discuss, GDP increases with increasing power, not energy.

For the purposes of this book, this is as complicated as we need to get to distinguish between energy and power. Now knowing this difference, some additional energy terminology will help the novice reader navigate concepts in this chapter and the rest of the book.

Energy Terminology

The highest level of accounting for human appropriation of energy is termed as *primary energy*. *Primary energy consumption* and *total primary energy supply* are

[16]Power (P) equals energy (E) divided by the time (t): $P = \frac{E}{t}$. Energy equals power multiplied by the time during which power was consumed: $E = P \times t$.

terms used to represent the total quantity of energy we extract from the natural environment, and ultimately dissipate as heat or convert to useful work. As you will read later in this chapter, in recent years U.S. primary energy consumption has been about 100 exajoules (EJ) of energy over the course of 1 year. Alternatively we can say that the U.S. dissipates power at the average rate of nearly 100 exajoules per year. Both statements are equivalent as when we refer to the term primary energy, the "consumed over the course of one year" is often implied.[17]

In addition to primary energy, the term *secondary energy* is used to refer to the energy content in energy carriers. For the most part, consumers like you and I purchase energy carriers, or secondary energy, and not primary energy. Energy carriers are the forms of energy consumed at the point they are converted to useful work (and heat) that provides some desired service (see Fig. 2.1). Example

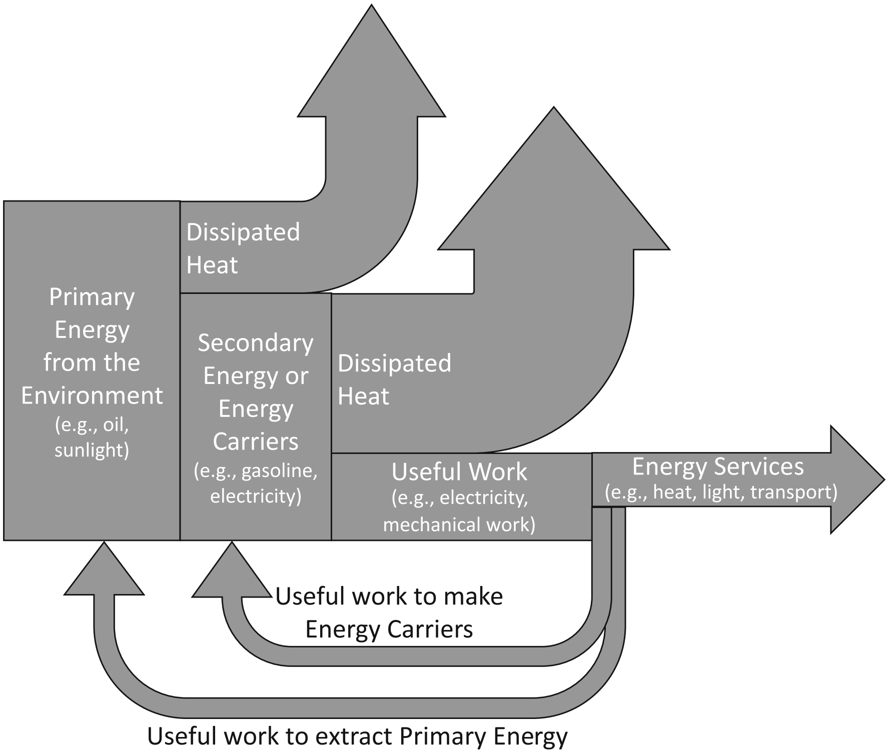

Fig. 2.1 Primary energy extracted from the environment is converted into secondary energy carriers that are then consumed to produce useful work to provide energy services. Some useful work is required to extract primary energy itself, and make energy carriers

[17]U.S. energy consumption for 1 year = (100 EJ/year) × (1 year) = 100 EJ. 1 EJ = 1×10^{18} J and 1 J is one "joule" of energy.

secondary energy carriers are the gasoline you put in your car, the natural gas that heats your home, and the electricity that turns on your lights and charges your mobile phone. This primary to secondary to useful work concept is relevant for understanding how energy data sets are compiled and used in economic analyses. The concept also gives insight for understanding the efficiency of using energy from the beginning to the end of the supply chain.

For those that want to understand additional details on units of energy and power, as well as differences among how agencies actually count primary energy, see the Appendix. There I summarize the different methods for counting primary energy consumption. You do not have to know the energy accounting methods to comprehend the content in this book, but it provides the background on why there is no one number for total energy consumption.

To obtain a feel for the *cost* of energy, this chapter compares primary energy consumption to GDP, or net economic output. Before we do this, the next section provides a quick summary of the GDP metric itself.

A Brief Description of GDP

In the following sections describing energy and food data, I use gross domestic product, or GDP, data to provide context and a metric for the cost of food and energy. This metric is spending on food and energy divided by GDP, and it proves to be very insightful. Practically, because historical time series estimates of GDP exist, energy spending per GDP is one of the few long-term metrics we can calculate for representing the feedback of the energy system on the economy.

The original concept for GDP developed in the U.S. in the 1930s. GDP is equal to the total monetary value of all final goods and services that have been exchanged within a country, usually specified for a year. GDP increases by exporting goods and services. It decreases by importing. When businesses invest more, consumers purchase more, and the federal government spends more, GDP increases. Because each of us decides to buy any given good or service at the price presented, in theory our consumer purchases include how much we "value" what we purchase. If something is not worth the price, then we can choose not to make the purchase, and GDP is lower than if we did make the purchase. If we do not make enough purchases of certain goods and services, businesses will stop producing and investing in them, and GDP goes down. Thus, much of GDP is supposed to be an aggregate measure of what consumers value and sellers produce. If GDP is higher, then it must be because the economy is producing output that people increasingly want. Right?

However, GDP as a metric itself has several limitations.

While GDP is a pretty good metric for the production of physical stuff, from its beginning GDP was never intended to be a measure of social welfare. That is to say, if GDP or GDP per person is larger in a given country, that does not necessarily mean that there is more social welfare, longer and healthier livelihoods, or more happiness and contentment. Most of what we hear in political and economic discourse in the news is the GDP growth rate, or lack thereof during recessions. Citizens are led to believe that growing GDP is always good, and declining GDP always bad. This is not strictly true, but various well-being indicators (e.g., literacy levels, health outcomes) do correlate well with increased GDP and energy consumption . . . up to a point. The literature shows that up to certain per capita levels of GDP and energy consumption, many well-being indicators increase, but after that point there are minimal gains (see various metrics in [28]). These indicators include child mortality, life expectancy, and literacy rates. An approximate threshold seems to be about 100 gigajoules of primary energy consumption per person (GJ/person). Below this number, certain indicators tend to be low, and above it they tend to be high but do not increase much with higher energy consumption. For reference, the U.S. consumes about three times this (arbitrary) threshold, and the European Union consumes about 130 GJ/person.

A second major limitation is that GDP measures a rate of economic output, not the amount of wealth within a country. GDP also measures some amount of produced "bads" as well as "goods." One example is war activity. GDP increases with increased production of "goods" such as missiles and aircraft specifically used to destroy both man-made and natural capital. When you destroy these capitals you remove the services they provide, thus producing bads by subtracting goods. As some say, with war, it is "our" missiles destroying "their" wealth. However, we can do it to ourselves. Advertising that promoted increased smoking and other unhealthy lifestyles increased GDP since more cigarettes were sold, more people were treated for cancer, and more jobs and technology were created to treat cancer. However, smoking reduced the value of our human and natural capital by increasing rates of cancer. Fortunately, in the case of smoking, much of the Western world has limited advertising for smoking as a tactic to reduce the occurrence of cancer. Herman Daly referred to increasing GDP by producing more bads as "uneconomic growth." [2]

Another major limitation of GDP is that while the phrase or acronym stays the same, its mathematical and economic definition has not. An easy example to discuss is computers. Clearly we could not consider the economic output from making computers in the year 1900 because there were no computers in 1900. Today we know there is some economic value from making, and using, computers including mobile devices. The invention of new goods affects the calculation of GDP because at first you do not know about them to include them in the calculation. Thus, there is a delay in counting contributions from new products and services.[18] However, it is even trickier than that. Old goods and services that were not counted as economic output might become included at later dates. One good example of this is prostitution. A few years ago the European Union started counting prostitution (the world's "oldest profession"), and illegal drugs, as part of GDP.[19] Further, U.S. states

[18]Robert Gordon discusses this problem at length in [13].

[19]New York Times (2014), Sizing Up Black Markets and Red-Light Districts for G.D.P.: https://www.nytimes.com/2014/07/10/business/international/eu-nations-counting-sex-and-drug-trades-toward-gdp.html UK Daily Mail (2014), Who said crime doesn't pay? Counting prostitution

are increasingly legalizing marijuana to be openly grown and sold for recreational, not only medical, purposes. Again, this then establishes official state accounting of previously uncounted sales of a particular item, in this case marijuana.

From more theoretical and political perspectives, in *The Value of Everything* Mariana Mazzucato explains that before 1993, statistical agencies did not count banking and financial services toward GDP: "…until the 1990s the services it [the banking sector] represented were assumed to be fully consumed by financial and non-financial companies, so none made it through to final output. The 1993 SNA [System of National Accounts] revision, however, began the process of counting FISIM [financial services] as value added, so that it contributed to GDP. This turned what had previously been viewed as a deadweight cost into a source of value added overnight. The change was formally floated at the International Association of Official Statistics conference in 2002, and incorporated into most national accounts just in time for the 2008 financial crisis."[20] For most of history, paying interest on loans, was seen as a non-productive cost of business, not a productive way to make money.

Practically all changes to GDP measures make the metric appear larger, not smaller, than it would otherwise be. Is an economic metric that always grows really what we want? Will we redefine GDP as needed such that it always grows? I will not now digress on this important philosophical topic of whether there is or should be some economy-wide number, such as GDP, that we inherently seek to maximize. Chapter 8 discusses how we might consider the economy as "seeking" to maximize something, but we have a while to go before we get to that topic. Part III summarizes reasons why some pose the use of alternative metrics of "progress." For more thorough discussions of the history and limits of using GDP as a metric, I refer you to other literature that provides context and in-depth discussion of that matter [1, 14, 15].

---

and drugs in the GDP figure has seen the UK's economy overtake France as fifth largest in the world: http://www.dailymail.co.uk/news/article-2888416/Who-said-crime-doesn-t-pay-Counting-prostitution-drugs-GDP-figure-seen-UK-s-economy-overtake-France-fifth-largest-world.html.

[20] Banking services are encompassed within FISIM. "The cost of 'financial intermediation services, indirectly measured' (FISIM) is calculated by the extent to which banks can mark up their customers' borrowing rates over the lowest available interest rate. National statisticians assume a 'reference rate' of interest that borrowers and lenders would be happy to pay and receive (the 'pure' costs of borrowing). They measure FISIM as the extent to which banks can push lenders' rates below and/or borrowers' rates above this reference rate, multiplied by the outstanding stock of loans.

The persistence of this differential is, according to the economists who invented FISIM, a sign that banks are doing a useful job. If the gap between their lending rates and borrowing rates goes up, they must be getting better at their job. That is especially true given that, since the late 1990s, major banks have succeeded in imposing more direct charges for their services as well as maintaining their 'indirect' charge through the interest-rate gap.

According to this reasoning, banks make a positive contribution to national output, and their ability to raise the cost of borrowing above the cost of lending is a principal measure of that contribution." [23, pp. 107–108].

Energy Consumption: How did We Get to Today?

The rest of this chapter presents three major trends of primary energy consumption for three different geographies. The first trend is gross primary energy consumption, the second is energy cost relative to GDP, and the third is food cost relative to GDP. The three geographies are England and the United Kingdom (U.K.), the United States of America (U.S.), and finally the world overall.

In this section I consider the quantification of absolute trends in energy consumption but not food consumption for all geographies. However, I do describe some food consumption within the U.K. and describe cost data for both energy and food. In doing this, I focus on the most core of Maslow's Hierarchy of Needs: physiological. Essentially, this means that if we do not have air, food, water, and shelter, then our survival is in such jeopardy that we do not have time to worry about social problems. This sentiment underpinned the modeling and worldview of *The Limits to Growth* authors: "Food, resources, and a healthy environment are necessary but not sufficient conditions for growth. Even if they are abundant, growth may be stopped by social problems." [24] Research supports that people do report being happier with more income to be secure in basic necessities, but higher incomes that support additional consumption and more luxurious items do not increase happiness much after the basic needs are met [22].[21] Let us dive into the energy and food data in the context of being necessary, but not sufficient for addressing social goals.

By observing these energy data across time for the three geographic scales, we understand the fossil energy transition within the first industrialized nation (the U.K.), energy trends within the post-World War II global power (the U.S.), and the energy production and costs in the context of the entire world. The world context is extremely important to understand each country's position in the global economy. We must always ask ourselves if each country in the world can develop along similar pathways as those demonstrated for the U.K. and the U.S.

The major purpose of presenting the energy consumption and cost data in such detail is to emphasize that there is one assumption about these energy trends that many analysts and policymakers take for granted, but that it is irresponsible to do so. Sometimes this assumption is a deliberate component to their narrative and worldview, but sometimes the assumption does not represent a conscious choice because individuals are unaware of its importance.

The incorrect assumption I speak of is that energy and food costs will always decline, and because they always decline, energy and food have not constrained socio-economic outcomes. However, the long-term data of this chapter show that:

> in the context of industrialization, *energy plus food costs are no longer declining*.

[21] Page 59 of [22] states: "...when money is relatively scarce, money buys happiness; when it is relatively plentiful, it ceases to do so."

This trend is a relatively new, important, and unappreciated indicator of the state of the world. Declining relative energy and foods costs (spending divided by GDP or income) are a defining characteristic of the industrial and fossil fuel era. No matter if you consider the U.K., U.S., or the world, spending on food and energy relative to economic output declined with industrialization until around the year 2000. For over 15 years since that time, we have been unable to continue this declining cost trend that many proponents of the techno-optimistic economic narrative assume continues irreversibly in an infinite world. In addition to looking at total energy costs in this chapter, Chap. 3 looks at the price of oil to further explore whether its cost has a clear ever-declining trend and to discuss price as an indicator of resource scarcity.

Before we can fully decipher the contemporary narratives of energy in Chap. 3, we must first consider the historical energy and economic data.

The United Kingdom

Primary Energy Consumption—U.K.

Perhaps the best way to envision the long-term change in both primary energy consumption and energy costs is by looking at a long historical time series of energy consumption and costs. Thanks to Roger Fouquet at the London School of Economics, we have estimates of England and the United Kingdom energy consumption and spending on energy since the year 1300.[22]

In Figs. 2.2, 2.3, 2.4, and 2.5 we see that pre-industrial England and U.K. were dominated by three types of biomass fuels: wood, fodder, and food for physical labor of humans. In terms of the pre-industrial energy services provided by biomass fuels, wood was primarily used for domestic heating (including cooking). Fodder refers to biomass and silage fed to animals that performed physical work. Fodder is still a sizable percentage of fuel in many developing countries. Fodder and food were the fuels for animals and people (that provided physical labor power), respectively [7]. This power was largely used in the fields for farming to grow the fodder and food itself. In 1700, England's economy consumed about 0.13 exajoules (EJ) of energy. 1 EJ is a billion billion joules, and burning one kitchen match releases about 1000 joules. Thus, the amount of energy that England consumed in 1700 was about *130 billion kitchen matches*. Since 1700, coal and other fossil fuels dominate primary energy consumption for all energy services, primarily the provision of heat and physical power via steam engines during the Industrial Revolution. The peak U.K. primary energy consumption occurred in 1973 at about 10.4 EJ, equivalent to burning *10 trillion kitchen matches*!

[22]The United Kingdom came into existence in 1707 by merging the Kingdom of England, including Wales, with the Kingdom of Scotland.

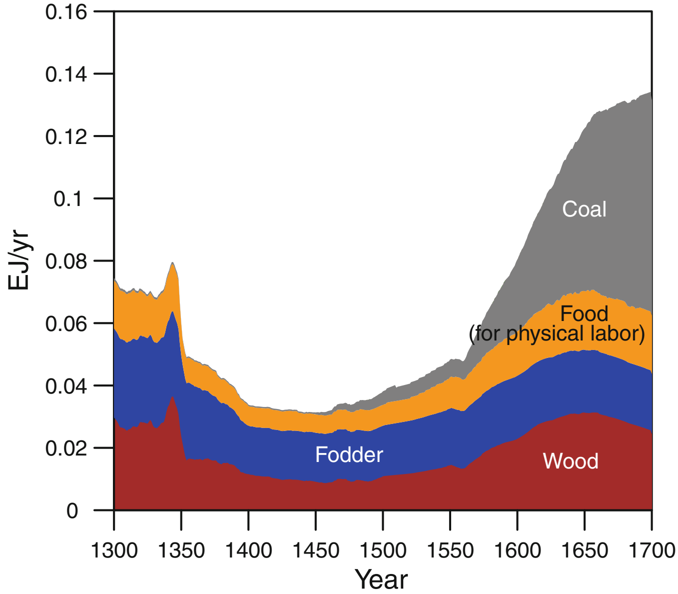

Fig. 2.2 The annual energy consumption (EJ/year) for England and the United Kingdom [9]. The fuels before 1700 were wood (brown), fodder (blue), food for physical labor (orange), and coal (gray). EJ = exajoule: 1 EJ = 1×10^{15} J

The percentage of the England/U.K. energy supply derived from biomass energy was practically 100% before 1450 and still greater than 85% in 1550 [8, 9]. This fraction dropped steadily to nearly 13% by 1830 with the rapid increase use of coal starting around 1600 (see Fig. 2.3). Note that this increase in coal use started well before the invention of the steam engine in 1712 by Thomas Newcomen and James Watt's design in 1769 that was the basis for the Industrial Revolution. This is because coal was already beneficial for domestic heating before engines existed [7].

But make no mistake, the steam engine undoubtedly affected trajectory of human history by spawning our modern economy. Here is a short story of how it all started.

In 1866, William Stanley Jevons stated in *The Coal Question*: "The terms in which the [steam] engine was described, and the way in which it was actually used for nearly two centuries, show that the raising of water out of our [coal] mines was the all important . . . purpose."[23] Industrialization accelerated because coal was burned in steam engines, steam engines operated water pumps, the pumps removed water from coal mines, and dry coal mines enabled access to more coal deposits and higher rates of mining that increased the flow of coal output from the production cycle. Thus, there was a motivation to describe how these steam engines actually functioned in order to engineer them to be more powerful and efficient and

[23] Jevons [16, p. 98].

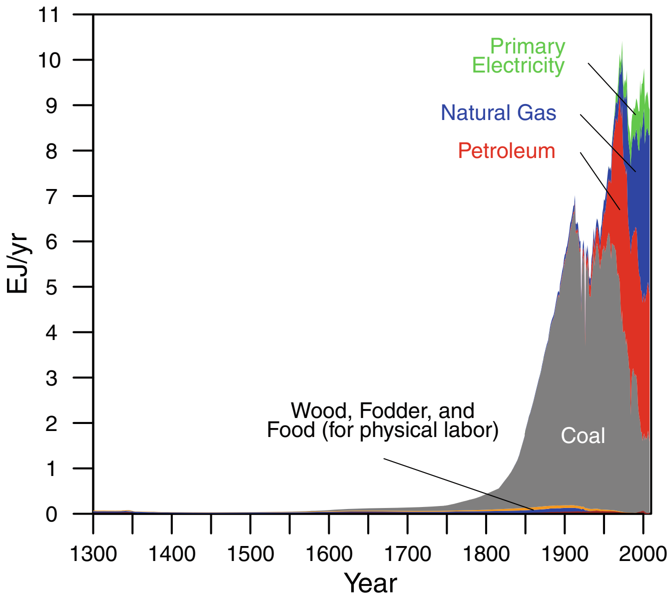

Fig. 2.3 The annual energy consumption (EJ/year) for England and the United Kingdom from 1300 to 2008 [9]. Primary electricity includes hydropower, nuclear, wind power, and solar power. EJ = exajoule: 1 EJ = 1×10^{15} J

accelerate the process faster again. As stated earlier, the laws of thermodynamics were largely derived from this need to understand the function of the steam engine. The medium defines the message.[24] Coal is the medium that became synonymous with early industrialization and accelerating economic growth.

Coal combustion was responsible for nearly 80% of primary energy consumption before natural gas, petroleum, or primary electricity (e.g., hydropower) played any role.[25] After World War I, petroleum started to dominate consumption. After World War II, natural gas and primary electricity increased in use to take appreciable shares of total primary energy provision. By the twenty-first century, the share of coal use dropped to approximately 20%, and in 2000 U.K. coal consumption was 3% of its peak that was reached during World War I.

[24]"The medium is the message" was a phrase coined by Marshall McLuhan and described in Chapter 1 of *Understanding Media: The Extensions of Man* by Marshall McLuhan, 1964.

[25]Fouquet's primary energy data assume the partial substitution method for translating primary electricity to thermal primary energy units.

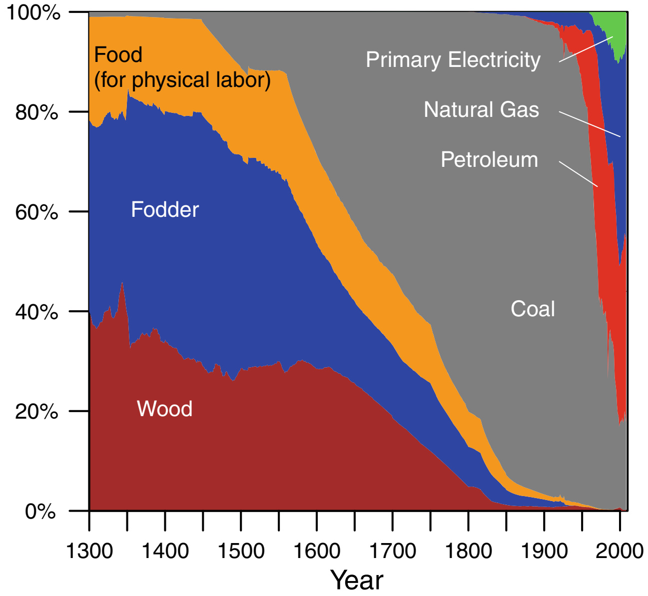

Fig. 2.4 The annual energy consumption by percentage of fuel for England and the United Kingdom from 1300 to 2008 [7, 9, 10]. Primary electricity includes hydropower, nuclear, wind power, and solar power

Spending on Fuels—U.K.

The dramatic rise in U.K. primary energy consumption starting in the 1800s coincides with an equally dramatic decline in the cost of energy. Energy consumption increased because energy became much cheaper and more abundant. I do not mean cheaper by a little bit, but cheaper by a wide margin. In using the word *cheap*, I refer to spending on energy relative to GDP. By spending I refer to expenditures by industry to produce food and energy and/or consumer purchases of energy and food.

Figures 2.5 and 2.6 show England and U.K. spending on energy, and it is well worth discussing the data at some length. I know of no other data set estimating the cost of energy that spans a longer time period. First and foremost, the numbers are much higher on the left side than on the right side of the figures. Energy was relatively expensive before the 1800s, and it has been relatively cheap since the mid-1900s.

The pre-industrial English economy (1300 to about 1800) typically spent between 30% and 40% equivalent of its GDP for what we might today call "energy" in the form of fuels (see Fig. 2.5) that *do not* include food for humans performing physical labor. When we include food as a fuel input for humans to perform physical labor, then this cost of energy jumps to 50–60% relative to GDP. In order to discuss pre-industrial society we must consider food as an energy resource, a fuel, for

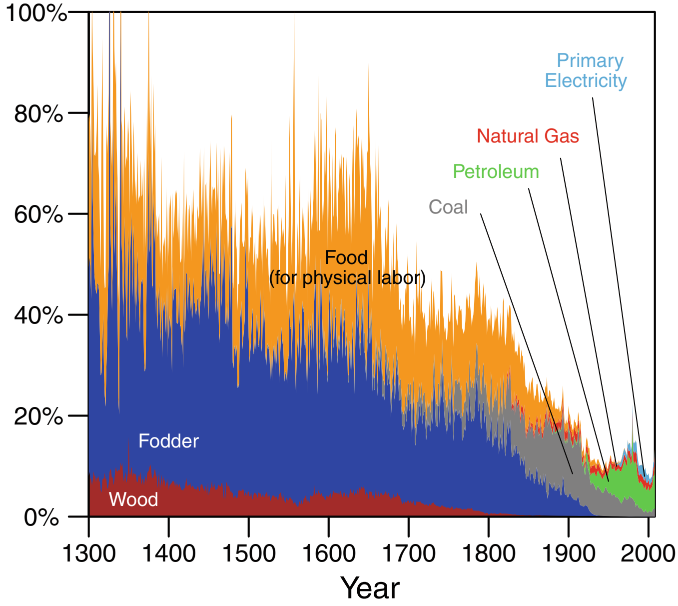

Fig. 2.5 The plot represents expenditures on energy, by type of fuel, divided by GDP for England/U.K. Included is food consumed by humans for performing physical labor. Data from Roger Fouquet [7, 9]. Primary electricity includes hydropower, nuclear, wind power, and solar power

preforming physical labor. In fact, fodder (biomass feed for animals) and food dominate the cost of energy up until around 1800. Food for humans and fodder for animals are the fuel sources, and muscles were the dominant *prime movers* of the pre-industrial era that provided useful work as power over the course of the day.[26]

We can see this dependence upon muscles for power needs in Fig. 2.6. This figure shows the same calculation as in Fig. 2.5 in terms of spending on energy divided by GDP. However, this time, it shows the results in terms of the cost of fuels to provide different *energy services* instead of the cost per type of each fuel itself. Ultimately, we seek energy services, and not necessarily energy itself. The various energy services that we seek are generally categorized as power (stationary useful work), heat (for industry and domestic homes), transportation (moving people and freight from place to place), and light [7, 9, 10]. That is to say, I can spend one hundred dollars to purchase natural gas, but 50 dollars of natural gas can go to provide heat while the other 50 dollars goes to provide power. All $100 would show up as spending on natural gas in Fig. 2.5, but in Fig. 2.6 $50 would show up as spending for power and $50 would show up as spending for domestic heat.

[26]Prime movers are devices that convert fuel, consumed at some rate, into force and motion, or power output.

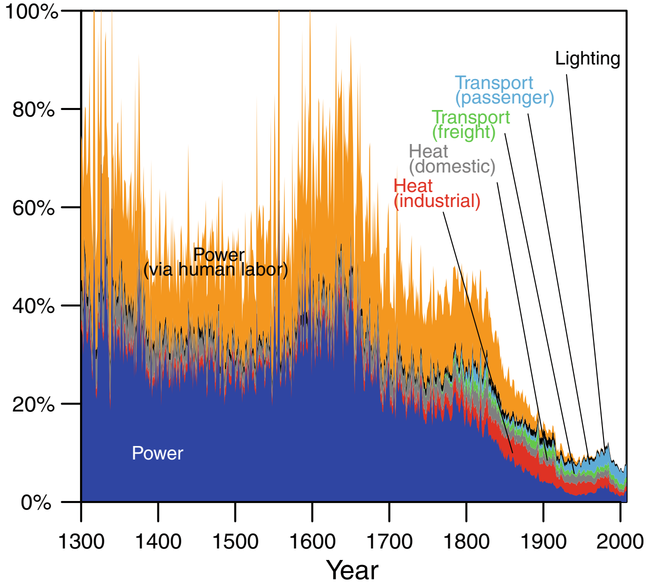

Fig. 2.6 The plot represents expenditures on energy, divided by GDP for England/U.K. from 1300 to 2008, for purchasing energy for services of industrial power, industrial heating, domestic heating, freight transport, passenger transport, and lighting. Included is food consumed by humans for performing physical labor. Data are from Roger Fouquet [7, 9]

The two time periods (the early 1300s and early 1600s) in which spending on energy was more than 60% of England GDP also correspond to times of higher population pressure relative to native food supply [30]. Thus, more people put more pressure on food and biomass resource costs.

During the time in which spending on energy was relatively high, until about 1800, the English economy grew at a slow rate of less than 1%/year for both real GDP/year and real GDP/person/year [7, 10, 12]. In effect, pre-industrial society was "power-limited" because physical power was provided primarily by muscles fed by fodder (animals) and food (people). Further, these biomass fuel sources grew at a rate limited by the sunlight, land area, and existing technologies and practices to grow biomass.

The cost of energy, including food for labor, in the U.K. did not fall below 30% relative to GDP until the 1840s. During this time the absolute energy dissipated from biomass consumption increased considerably, but coal consumption increased at a much more rapid rate, thus taking over the majority of the primary energy mix. After the 1840s the relative cost of energy dropped quickly for 80 years through the 1920s, eventually to below 10% during World War II, as the benefits accumulated from investments associated with the Industrial Revolution and fossil fuel consumption.

While the United Kingdom has the longest string of data on energy consumption and costs, allowing us to track patterns from a pre-industrial to post-industrial economy, we know the Industrial Revolution did not stay within the confines of the British Isles. All developed nations went through similar transitions in using fossil energy and hydropower to release themselves from the burden of energy and power constraints. For example, Sweden's spending for energy (including food and fodder for animate power) relative to its GDP also consistently declined from 90% in the early 1800s to less than 20% after 1925 as Sweden shifted from biomass to coal [17, 29]. I now turn to discuss energy consumption and cost trends for the United States.

The United States: Post-World War II Superpower

Primary Energy Consumption—U.S.

The United States went through a similar, but faster, transition as did the U.K. in terms of increasing use of coal. One major difference is that the colonists (before the U.S. was a country) on the eastern seaboard of North America did not use appreciable amounts of coal. The U.S. did not start using significant quantities of coal until the mid-1800s, over two centuries after coal was of significant use in the U.K. Because of the later use of coal, the U.S.'s transition from a biomass to fossil-dominated economy was faster than that of the U.K.

U.S. total primary energy consumption increased tremendously from the late 1800s until around 2000. Figure 2.7 indicates that major changes in the trends of increasing energy consumption coincided with the Great Depression, the two oil "crises" in the 1970s (discussed in Chap. 3), and the mid-2000s as the time of highest energy consumption through 2018. As the data in Fig. 2.7 come from the EIA, the conversion of electricity from hydroelectric, wind, and solar power assumes the partial substitution content method. (See Appendix for details about different accounting methods for primary energy.)

In broad terms, U.S. primary energy consumption increased at an exponential rate of about 3%/year from 1900 to 1973. It increased approximately linearly at +1 EJ/year/year from 1973 to 2000, and stayed approximately constant since 2000. It is important to understand these changes in trend (first increasing quickly from 1900 to 1973, then increasing more slowly from 1973 to 2000, and then stagnating from 2000 to present) within the context of the dynamics of both U.S. and global economic and demographic factors. This discussion, however, must wait until Chap. 5 after introducing some of these non-energy trends in Chap. 4.

As a share of U.S. primary energy consumption, coal peaked in the first decade of the 1900s near 75% (Fig. 2.8), but in total rate of consumption coal peaked in 2005 at 24 EJ/year. That is to say, even though the *fraction* of coal use peaked at the beginning of the twentieth century, the *rate* of coal consumption peaked at the beginning of the twenty-first century. Thus, a "transition" in share is not the same as "transition" in quantity or rate of use.

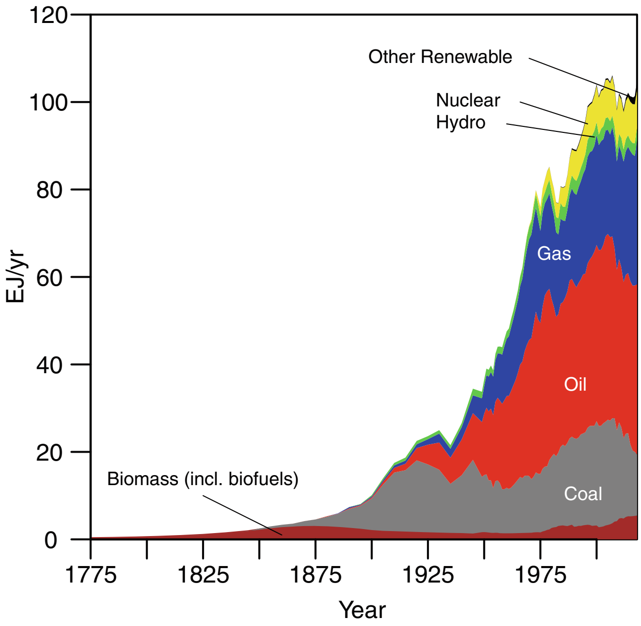

Fig. 2.7 U.S. primary energy consumption (EJ/year) by fuel from 1775 to 2018 [Energy Information Administration, Monthly Energy Review, Table 1.3 and Appendix E]. Biomass includes liquid biofuels. Other renewable includes primary electricity from geothermal, wind, and solar power plants. EJ = exajoule: 1 EJ = 1×10^{18} J

The highest shares of oil and natural gas consumption occurred in mid-1970s and early 1970s at 48% and 32%, respectively. Through 2018, the highest absolute rate of energy consumption from oil was in 2005 (42 EJ/year) and from natural gas was in 2018 (33 EJ/year). As with coal, the highest shares of use of oil and natural gas are not coincident with the highest absolute rates of their consumption. Thus, a higher share for a primary energy resource does not necessarily mean there was more absolute consumption of that resource.

Since 1981 the U.S. share of consumption from each fossil fuel has remained within a relatively constant range: coal from 13% to 23%, oil from 35% to 42%, and natural gas from 22% to 31%. However, since 2014, the share of coal declined to the lower end of its range, and natural gas to the higher end of its range. For the last decade both natural gas and renewable energy consumption have increased while the total primary energy consumption rate of the U.S. has remained relatively constant, between 99 and 106 EJ/year, since 1996. After 2008, increased horizontal drilling with hydraulic fracturing in tight sand and shale formations extracted increasing quantities of natural gas that displaced significant quantities of coal use for power generation [4].

Since declining below 10% of the total in the 1920s, the share of total renewable power has typically been between 6 and 8 percent. Total hydropower generation

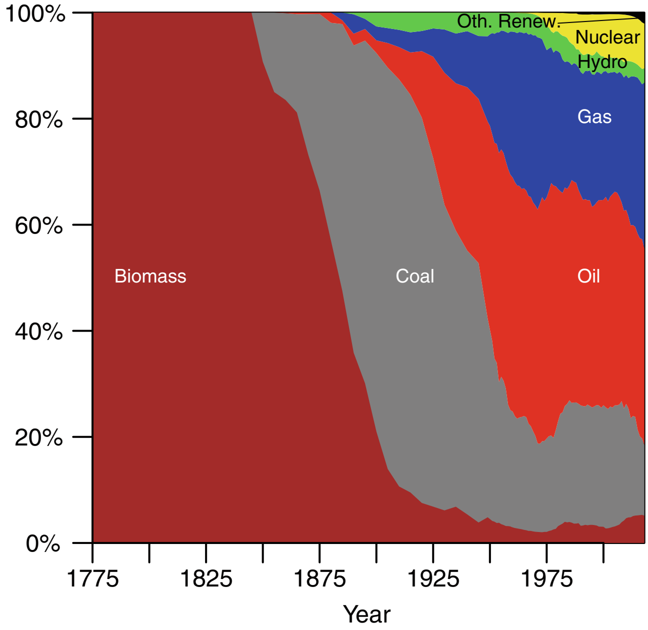

Fig. 2.8 U.S. primary energy consumption by percentage of each fuel from 1775 to 2018 [Energy Information Administration, Monthly Energy Review Table 1.3 and Appendix E]

(e.g., in kWh) increased through the 1970s, but has remained flat since. Liquid biofuels (e.g., ethanol and biodiesel), wind and solar power are responsible for increasing the share of total renewable energy consumption above 8% since 2009. The absolute rate of consumption of renewable energy has seen a slow but steady average increase of less than 0.1 EJ/year/year from 1990 through 2007 and approximately 0.5 EJ/year/year since 2007. In 2017, total renewable energy consumption was above 10 EJ/year for the first time in U.S. history.

Nuclear power in the U.S. rose quickly from the mid-1950s until the 1990s as the only major wave of nuclear construction commenced after World War II. The share of nuclear power peaked at just under 9% in 2009 roughly coincident with its maximum absolute quantity of production of just under 9 EJ/year in 2007–2010. Since 1999, nuclear energy consumption has been greater than 8 EJ/year but it did not increase substantially after that point, and it is expected to decline in the near term due to expectations of power plant retirements along with few to no new reactors coming online. As of the time of this writing, there are only two new reactors in construction (Vogtle power plant reactors 3 and 4 in Georgia), and in 2017 construction was halted for two other reactors that had begun construction at the same time (V.C. Summer reactors 2 and 3). Chapter 3 summarizes the reasons why we are unlikely to see near-term increases in nuclear power in the U.S.

Spending on Fuels—U.S.

The declining energy and food cost trends witnessed for the U.K. are repeated in the U.S. The United States post-World War II era is characterized by a continuous decline in relative food costs until 2006, and a decline in combined food and energy costs from the 1930s until around 2000. This trend holds from two perspectives of energy spending.

First, consider "consumer expenditures" on food and energy goods and services relative to GDP (Fig. 2.9a). As a category, consumer expenditures are the largest of the components that are summed to estimate GDP.[27] Consumer food expenditures and prices refer to what you and I pay at the grocery, and these prices include the cost to produce food in addition to transportation, storage, packaging, and marketing. Consumer energy expenditures refer to our purchase of fuels such as

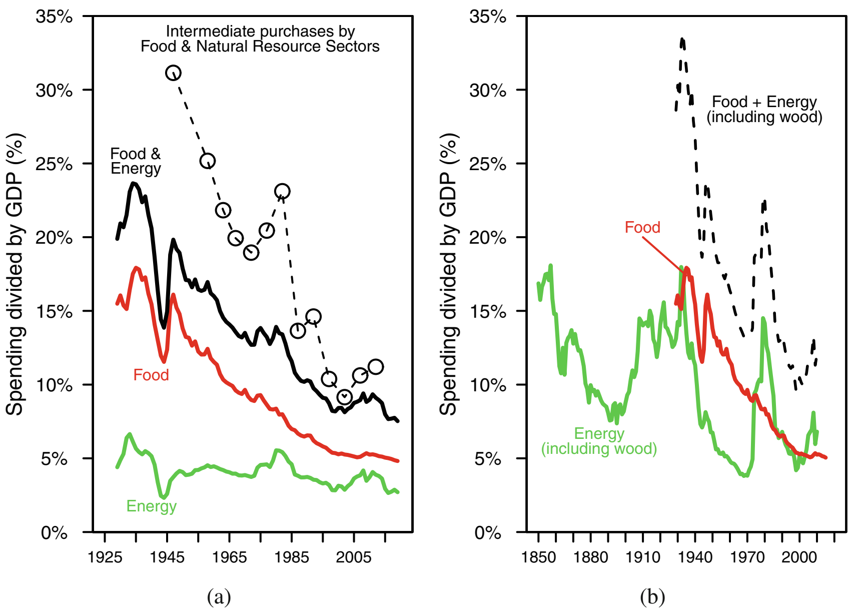

Fig. 2.9 U.S. spending on food and energy using two different energy estimates. (**a**) Energy and food data are annual personal consumption expenditures from BEA Table 2.3.5. Food and resources sectors as intermediate purchases (open circles) are from BEA benchmark summary input–output tables as calculated in [20]. (**b**) Food data are annual personal consumption expenditures from BEA Table 2.3.5. Energy spending estimate, including for wood, is from Fizaine and Court [6]

[27] Gross Domestic Product, or GDP, is equal to the sum of (1) consumer expenditures, (2) investment by companies, (3) (federal and state) government expenditures and investment, (4) net exports (= exports − imports) of goods and services to other countries, and (5) change in inventories.

gasoline and electricity in our homes. However, consumer energy expenditures do not include total U.S. energy spending. For example, government spending on energy is excluded.

It is very important to note that *the majority of the long-term decline in total food and energy spending is due to declining food costs*. Historically, consumer food spending has been higher than for energy, but today is no longer the case. Figure 2.9a shows data from the Bureau of Economic Analysis (BEA) that indicates U.S. consumer spending on food was 18% of GDP in 1935, during the Great Depression, and approximately 5% of GDP for the last two decades. Relative to consumer spending on energy, food spending was two to three times larger from the 1930s to the 1950s, after which time consumer food spending per GDP declined through 2006. Since 2006, food spending per GDP has been approximately level near 6%.

The change in consumer spending for energy has not declined as dramatically as that for food. The consumer cost of energy goods and services has had a slow declining trend since the 1930s while averaging just above 4% of GDP and typically staying between 3% and 5%. The time periods of consumer spending significantly greater than 5% of GDP on energy generally correspond to times of declining or low economic growth (e.g., Great Depression, oil crises of the 1970s) As I will discuss in Chap. 3, seemingly small fluctuations in the cost of energy can have large ramifications depending upon the level from which they start. That is to say, increasing economy-wide energy expenditures 1% from 4% to 5% is largely unnoticeable, but changing 1% from 7% to 8% has been the difference between recession and growth (see the energy spending peaks in the 1970s and 2008 in Fig. 2.9).

A second way to consider food and energy costs is not by how much you and I (as "consumers") spend at grocery stores, restaurants, and gasoline stations, but by how much companies spend to provide the food and energy that we end up purchasing. We can calculate this spending by using data from the BEA that summarizes "intermediate" purchases,[28] or spending by the economic sectors associated with food and energy production. These sectors are those such as farming, oil and gas drilling, and electricity. Their collective spending is represented by the circles in Fig. 2.9a.[29] Spending by the food and energy sectors, relative to GDP, dropped from 31% in 1947 to 9% in 2002. In 2012, the last year with benchmark data, U.S. food and energy sectors spent an amount equal to 11% of GDP. Here again,

> *just as with the data for U.S. personal consumption expenditures, relative to GDP, the low point in U.S. intermediate spending for food and energy occurs in the early or mid-2000s.*

---

[28]These intermediate purchases are those that are used to provide final products to consumers like you and me.

[29]The BEA data presented here are derived from the benchmark input–output tables that are estimated approximately every 5 years.

Figure 2.9b uses a different estimate of energy costs as an additional comparison and verification of energy cost trends in the U.S. The food data are the same as in Fig. 2.9a, but the energy data more closely represent an estimate of the cost of primary energy supplies instead of only secondary energy carriers purchased by consumers. Further, the data estimate begins in 1850 and includes an estimate of the cost of wood used for energy. By including a cost estimate for wood, the pre-World War II energy expenditures increase substantially to typically 12–15%, and over 15% for the 1850s. This combined food and energy cost more closely matches the intermediate spending in Fig. 2.9a, and thus is also shown as a dashed line for easier comparison.

Just as with the combined energy and food estimates in Fig. 2.9a, those in Fig. 2.9b show a distinctive and clear declining trend from the 1930s until around the year 2000.

Thus, no matter how you slice the data for the U.S., we can declare that the cost of food and energy in the U.S. declined for 70 years after the Great Depression until about the year 2000. After that year, energy and food have no longer become less expensive, and on average they have been more expensive than in 2002.

The World

Primary Energy Consumption—The World

Figure 2.10 shows an estimate of global primary energy consumption from 1800 through 2012, and Fig. 2.11 shows the percentage share of each fuel type [6].[30] The conversion of electricity from hydropower, wind, and photovoltaics into primary energy assumes the partial substitution method.[31]

One striking difference between the data for the world and those of both the U.K. and the U.S. is that world primary energy consumption is still rising while that of the U.K. peaked in the 1970s and that of the U.S. has plateaued since the 2000s. Globally, each type of primary energy resource has increased in absolute rate of consumption until very recently. According to the BP Statistical Energy Review, 2014 marked the maximum energy consumption rate from coal worldwide, with the

[30] World primary energy data from [6] is stated as: "We retrieved global primary energy productions through the online data portal of The Shift Project (2015) which is built on the original work of Etemad and Luciani (1991) for 1900–1980 and EIA (2014) for 1981–2012. Prior to 1900, we completed the different fossil fuel time series with the original 5-year interval data of Etemad and Luciani (1991) and filled the gaps by linear interpolation. The work of Fernandes et al. (2007) and Smil (2010) was used to retrieve historical global consumption of traditional biomass energy (including wood fuel and crop residues but excluding fodder and traditional windmills and waterwheels)."

[31] See Appendix for summary of different energy accounting methods.

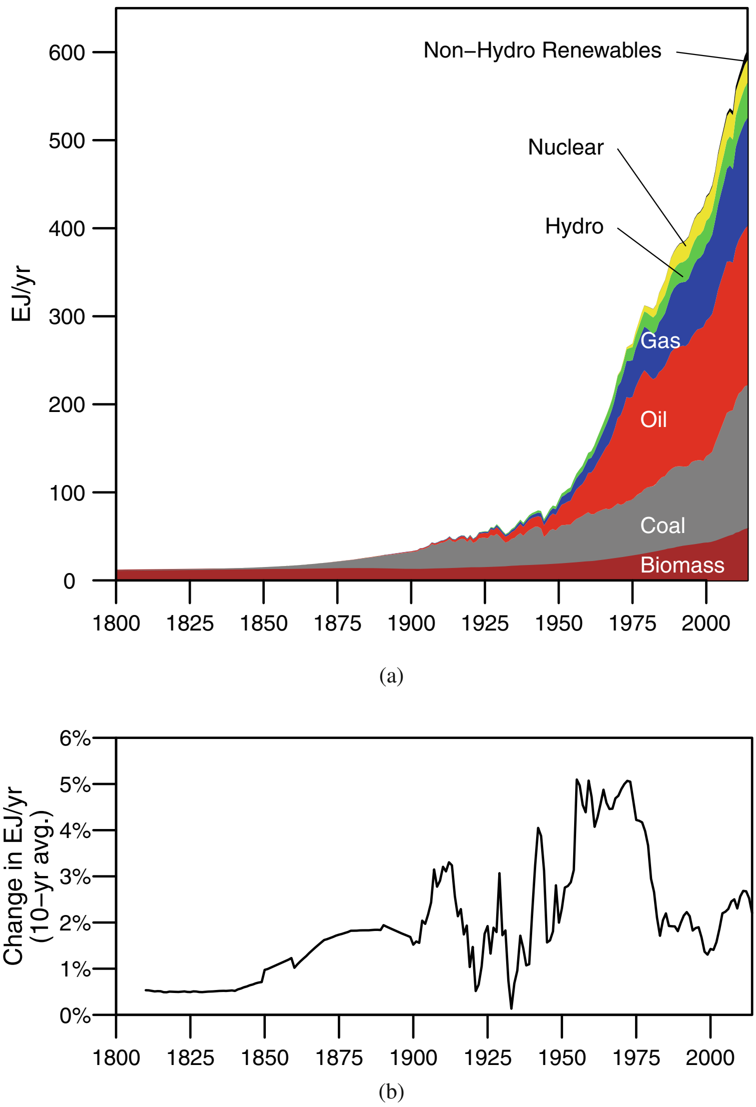

Fig. 2.10 (**a**) World primary energy consumption (EJ/year) per primary energy source from 1800 to 2014. (**b**) 10-year average growth rate in global energy consumption. Data from 1800 to 1899 as used in [6], and data from 1900 to 2014 from International Institute for Applied Systems Analysis Primary, Final and Useful Energy Database (PFUDB) [3]

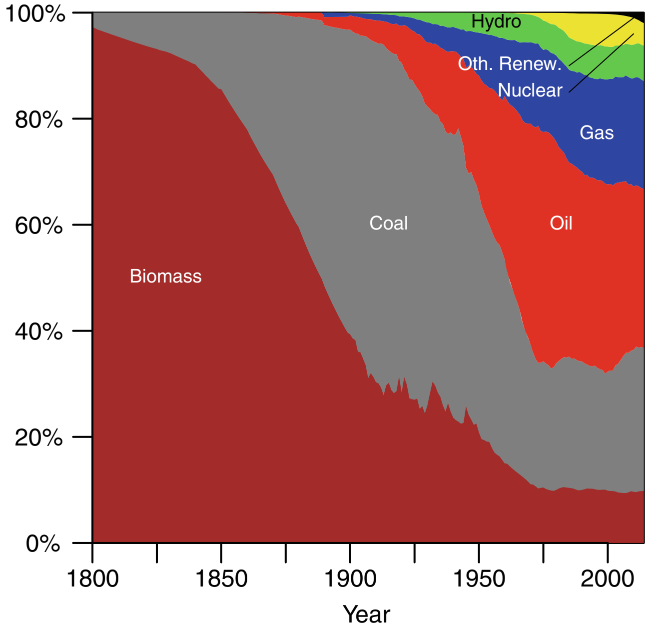

Fig. 2.11 The percentage of world gross primary energy consumption per each supply type from 1800 to 2014. Data from 1800 to 1899 as used in [6], and data from 1900 to 2014 from International Institute for Applied Systems Analysis Primary, Final and Useful Energy Database (PFUDB) [3]

rate of coal consumption declining from 162 EJ in 2014 to 156 EJ in 2017. However, they reported higher coal consumption of 158 EJ in 2018.[32] It remains to be seen if the decade of the 2010s exhibits the peak coal consumption rate as it would be the first time a fossil resource has peaked in the *absolute* rate of consumption since the industrial era. Some argue that the worldwide production rate of "conventional crude oil" peaked in the mid-2000s, and I discuss the disagreements over this matter in Chap. 3.

Another remarkable feature of world primary energy consumption is its rate of increase from 1955 to 1979. This is the only time in history that the 10-year running average growth rate in energy consumption was greater than 4%/year. The rapid increases in production of oil and natural gas drive this statistical trend, and the U.S. was the dominant player for extraction and consumption during this period.

In 1950, the U.K. and the U.S. combined for approximately 45% of total world primary energy consumption. This is amazing. The populations of the two countries represented 8.3% of world population yet commanded 45% of approximately

[32] BP Statistical Review of World Energy 2019, downloaded September 22, 2019 from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/xlsx/energy-economics/statistical-review/bp-stats-review-2019-all-data.xlsx.

100 EJ/year of worldwide energy consumption in 1950.[33] Also, during this time, the U.S. dominated worldwide consumption of oil, accounting for 65% in 1949 declining to 30% by 1979 even though the U.S.'s absolute consumption rate of oil increased through 1978. The U.S. command of oil and gas consumption in the two decades after World War II was enabled by its high domestic extraction. The U.K. did not become a major oil and gas extractor until the 1970s as it responded to the Arab Oil Embargo in 1973 and the OPEC oil price increase in January of 1974 by exploring and extracting oil and gas from the North Sea. Chapter 5 further explores the worldwide shift in energy systems caused by events in the 1970s.

The worldwide shift to different consumption of the different primary energy resources and technologies is qualitatively the same as for the U.K. and the U.S. Because early energy fossil energy consumption was dominated by the U.K. and the U.S. Thus, the U.S. and the U.K. largely determined the initial global shift to fossil fuels. I defer further discussion of the timing of the change in world energy mix until the Summary of this chapter.

Spending on Fuels—The World

Both the U.K. and the U.S. data indicate that energy and food costs declined since industrialization until the 2000s. The same trend also holds for the overall world economy.

Figure 2.12 shows two estimates for world energy expenditures since 1850 [6], and adds these to world food production costs from the Food and Agriculture Organization (FAO). The "no wood" data are estimates of marketed energy, primarily oil, natural gas, coal, and electricity from renewable and nuclear power. The cost estimate "including wood" uses data for wood prices in the U.S. to multiply by an estimate of global wood consumption.

One takeaway from Fig. 2.12 is that the cost of energy, including wood, typically fluctuated between 6% and 8% of global GDP from 1850 until the 1950s. Starting around the end of World War II, the cost of energy declined almost continually until 1970. In these data, the lowest cost energy (including wood) for the world was 4.0% in 1970 (the year of peak oil production rate in the U.S.), matched very closely in 1998 [6]. The post-World War II multi-decadal trends for spending on energy are largely dictated by swings in oil prices.

The FAO data show that, since the 1990s, the world cost of food production has kept declining, but at a much slower rate than before 1980. The FAO food cost estimate in Fig. 2.12 is that of cost of food production by farmers rather than food purchased by consumers like you and me. From 2007 to 2014, world food production costs per global GDP remained about the same at 3.6–3.8%, before

[33] United Nations, Department of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision, DVD Edition. File POP/DB/WPP/Rev.2012/POP/F01-1.

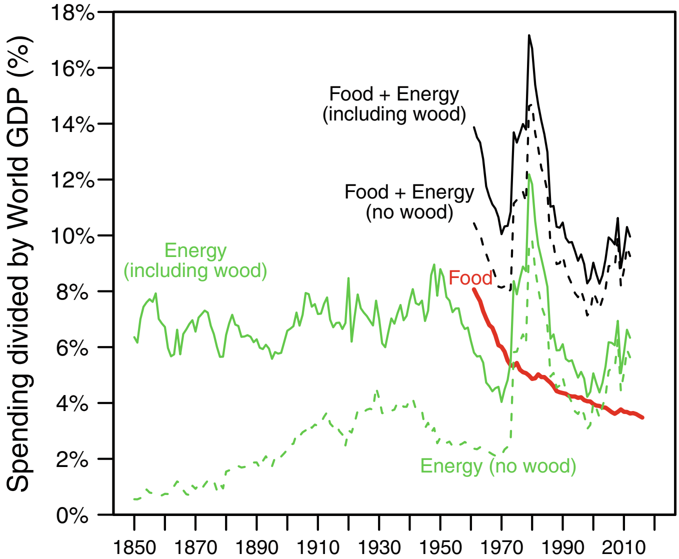

Fig. 2.12 World spending on energy (1850–2012) and food (1961–2016) divided by global gross domestic product (GDP) and expressed as a percentage. Data for energy costs are separated into time series that includes the cost of wood (solid lines) and without the cost of wood (dashed lines) from [6]. Data for food expenditures is from the Food and Agricultural Organization as World "Gross Production Value (constant 2004–2006 million US$)" for Food (item code 2054) divided by GWP from the World Bank. The food cost calculations before 1992 are shifted upward by the difference in the Gross Production Value of food from 1991 to 1992 because there are no FAO data for U.S.S.R (1991 and earlier) but there are FAO data for the states formed from the U.S.S.R starting in 1992. Thus, the shift is an estimate of the Gross Production Value of the U.S.S.R.

declining to 3.5% in 2015. While food has become quite cheap, it is approaching its lower limit. Thus, per Figs. 2.12 and 2.13,

> *the combined world energy and food expenditures data indicate the worldwide trend of energy and food costs as a share of global gross domestic product reached its minimum around the year 2000.*

Unfortunately, the data in Figs. 2.12 and 2.13 do not include fodder eaten by animals that perform work on farms as was the case in the UK data of Figs. 2.5 and 2.6. Thus, given the large share of energy costs for fodder (to produce power on the farm) in pre-industrial UK and England, we should expect that the global totals in Fig. 2.12 are likely 10–20% higher in 1850. We should also expect cost for fodder today is not zero due to a non-trivial portion of developing countries' agriculture still dependent on animate power for farming.

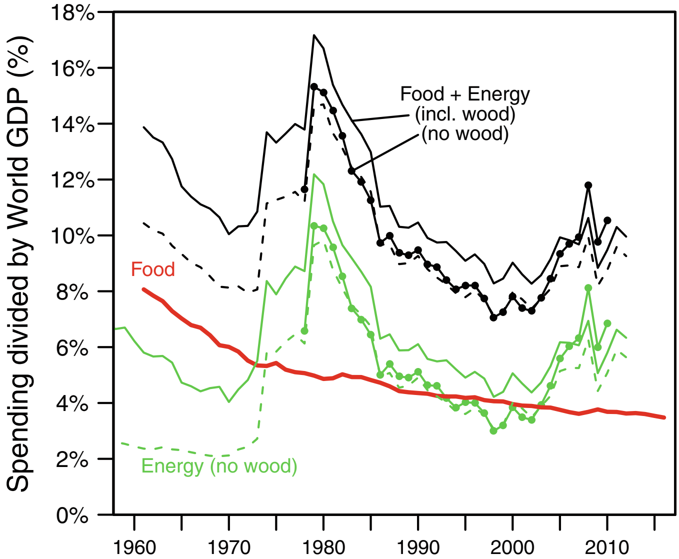

Fig. 2.13 World spending on energy (1961–2012) and food (1961–2016) divided by global gross domestic product (GDP) and expressed as a percentage. Data are the same as in Fig. 2.12 except for one additional time series for comparison of energy expenditures: energy expenditures data (for 1978–2010) represented by the thin lines with filled circles come from [21]

The fundamental shift in global food costs is also evident when considering consumer level prices instead of farm level prices, as in Fig. 2.14. Consumer food costs are represented by the FAO's Real Food Price Index. This index generally declines from the mid-1960s until around the year 2000. During that interval there is both a sharp rise in food costs in 1973 and 1974 and a sharp decline in food costs in 1985 and 1986. The price rise coincided with the Arab Oil Embargo in 1973 and the OPEC oil price increase in January of 1974. The food price decline coincided with declining oil prices that followed a decade of massive investments in both oil drilling and efficiency in use of oil (e.g., fuel economy standards for cars and no longer using oil to fuel significant quantities of power generation in OECD countries). These correlations show how coupled oil is to food production and distribution.

The FAO Real Food Price Index resides at its lowest levels from the mid-1980s until the mid-2000s. After 2005 the food index rises quickly, staying high until 2014 before dropping in 2015 and 2016 but staying above the 2006 value through 2019. *The FAO real food price index data show that world consumer food prices have increased since the early 2000s.* Thus, while producer costs might only be stagnating since the 2000s, consumer costs are on the rise.

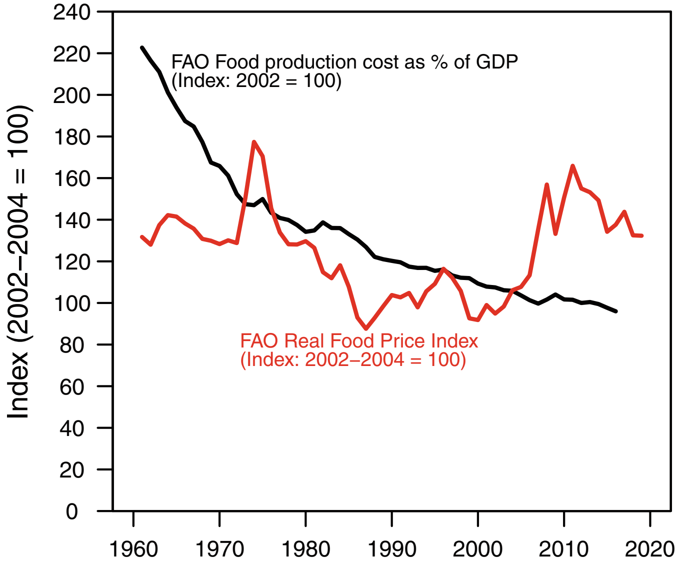

Fig. 2.14 World spending on food (1961–2016) expressed as an index with the year 2002 as index = 100. The black line is world FAO food production costs divided by gross world product (the same data as in Figs. 2.12 and 2.13), and the red line is the FAO Real Food Price Index (1961–2019). The Food Price Index represents *consumer level* spending which is larger than food production costs at the *farm level* due to additional costs of distribution, processing, and other services

Summary

Primary Energy Consumption and Energy and Food Costs

There are a few major takeaways from considering the historical data for both the consumption rates of primary energy and the cost of energy and food within the U.K., U.S., and world overall.

> *First, in the history of mankind, the cost of energy plus food has never been cheaper than around the year 2000.*

Up until that point in history, food and energy costs generally declined, greatly accelerated during the transition to the use of fossil-fueled machinery, and after that point they have approximately held steady (after a rise to 2008) from the producer perspective and increased from the consumer perspective. This shift away from declining costs holds whether we look at over 700 years of data describing England and the United Kingdom [10, 18], 200 years of data for Sweden [17], almost 100 years of data for the United States [5, 19], or the last 60 years of data for world food and energy costs [19, 21]. Thus, the combined cost of *food*, the fundamental input that allows people to live, and *energy*, the fundamental input that drives our economy, has crossed a major turning point during our current industrial and fossil fuel era.

Second, coal led the transition from a biomass to fossil economy, and this transition occurred first in the U.K., then the U.S., and then the world overall.

Third, while the world has experienced definitive shifts in *the share* of primary energy obtained from different sources, these shifts have typically come with increased *absolute* total primary energy consumption from each supply. Only very recently have we seen evidence for the possible decrease in the worldwide consumption rate of one energy source: coal. Historically, new sources of primary power have simply been additions to the existing sources, not replacements.

Fourth, the first region to reach its maximum total primary energy consumption was the U.K. in 1970, the second was the U.S. in 2005 (but relatively constant over the last 20 years), and the world has not yet experienced a peak in energy consumption (see Fig. 2.10). The fact that both the U.K. and the U.S. no longer consume more energy within their borders is important to consider in the contexts of broader megatrends (Chap. 4) and systems thinking (Chap. 5). That is to ask, if the U.K. (the first industrialized country, small in land mass and population) and the U.S. (a country with abundant energy resources, a large land mass, and the largest economy in the world since World War II) both peaked in energy consumption, then should we expect this to eventually occur for the world also?

Looking Backward to See Forward: Renewable and Fossil Energy Transitions

We simply cannot explain the current state of the world without considering the full context of the increase in the rate of energy consumption, and decline in the cost of this consumption, since industrialization. To consider energy over the course of more than 100 years, we have to consider food, fodder, and biomass as energy resources from which developed countries initially transitioned. In the pre-industrial age, most people were farmers. Food and fodder were the fuels that enabled human and animal (e.g., horses, oxen) muscles to perform physical work, such as plowing, grinding, and harvesting on the farm [28]. Before modern machines, animals and laborers were the major "machines" into which fuels were input to enable force and motion. With the advent of steam and internal combustion engines in combination with coal and oil, the course of history was changed.

While practically all disciplines and perspectives recognize the unprecedented enhancements from fossil fuel-driven machinery, they do not all recognize that these enhancements cannot increase indefinitely. Even though it is a fact that the Earth is finite, some holding the techno-optimistic economic narrative and fossil energy narrative see no limitation in our practical ability to advance technology to extract more technically challenging fossil energy and material resources. For many of those in the renewable energy narrative that also hold to economic technooptimism, they see a limitation in our fossil-powered society, either due to climate change or declining resource quality, but they do not see any similar limitation in our ability to extract renewable resources.

More often than not there is a belief in continuous technological innovation, but too often only for the energy narrative that one is promoting. Fossil energy narrative: We will always find more fossil energy and never run out, so we do not need renewable energy. Renewable energy narrative: Costs of renewable energy systems will decline indefinitely, just as have the costs for mobile phones, and costs for fossil fuels will eventually increase such that we will eventually and easily substitute renewable for fossil energy.

It is to a comparison of the two energy narratives that we now turn.

References

1. Coyle, D.: GDP: A Brief but Affectionate History. Princeton University Press (2014)
2. Daly, H.E.: uneconomic growth in theory and fact. http://www.feasta.org/documents/feastareview/daly.htm (1999). Online; accessed 1-February-2020
3. De Stercke, S.: Dynamics of energy systems: A useful perspective. Tech. rep., International Institute for Applied Systems Analysis (2014)
4. DOE: Staff report to the secretary on electricity markets and reliability. Tech. rep., U.S. Department of Energy (2017). https://energy.gov/sites/prod/files/2017/08/f36/Staff%20Report%20on%20Electricity%20Markets%20and%20Reliability_0.pdf. Accessed September 3, 2017
5. Bureau of Economic Analysis, U.S.A.: Personal consumption expenditures by major type of product, table 2.3.5 (2017). Accessed data Last Revised: January 4, 2017
6. Fizaine, F., Court, V.: Energy expenditure, economic growth, and the minimum EROI of society. Energy Policy **95**, 172 – 186 (2016). http://dx.doi.org/10.1016/j.enpol.2016.04.039. http://www.sciencedirect.com/science/article/pii/S0301421516302087
7. Fouquet, R.: Heat, Power, and Light: Revolutions in Energy Services. Edward Elgar Publishing Limited, Northampton, Massachusetts (2008)
8. Fouquet, R.: The slow search for solutions: Lessons from historical energy transitions by sector and service. Energy Policy **38**(11), 6586–6596 (2010). https://doi.org/10.1016/j.enpol.2010.06.029
9. Fouquet, R.: Divergences in long-run trends in the prices of energy and energy services. Review of Environmental Economics and Policy **5**(2), 196–218 (2011). https://doi.org/10.1093/reep/rer008
10. Fouquet, R.: Long-run demand for energy services: Income and price elasticities over two hundred years. Review of Environmental Economics and Policy **8**(2), 186–207 (2014). https://doi.org/10.1093/reep/reu002. http://reep.oxfordjournals.org/content/8/2/186.abstract
11. Georgescu-Roegen, N.: Energy and economic myths. Southern Economic Journal **41**(3), 347–381 (1975)
12. Gordon, R.: Is U.S. economic growth over? faltering innovation confronts the six headwinds. NBER working paper no. 18315 (2012)
13. Gordon, R.J.: The Rise and Fall of American Growth: the U.S. Standard of Living since the Civil War. Princeton University Press, Princeton, NJ (2016)
14. Heun, M.K., Carbajales-Dale, M., Haney, B.R.: Beyond GDP: National Accounting in the Age of Resource Depletion. Springer International Publishing (2015)
15. Jackson, T.: Prosperity Without Growth: Foundations for the Economy of Tomorrow, second edition edn. Routledge, Milton, UK and New York, NY, USA (2017)

16. Jevons, W.S.: The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines, second edition, revised edn. Macmillan and Co., London (1866). Kessinger Legacy Reprints
17. Kander, A., Stern, D.I.: Economic growth and the transition from traditional to modern energy in Sweden. Energy Economics **46**(0), 56–65 (2014). http://dx.doi.org/10.1016/j.eneco.2014.08.025. http://www.sciencedirect.com/science/article/pii/S0140988314002072
18. King, C.W.: Comparing world economic and net energy metrics, part 3: Macroeconomic historical and future perspectives. Energies **8**(11), 12,348 (2015). https://doi.org/10.3390/en81112348. http://www.mdpi.com/1996-1073/8/11/12348
19. King, C.W.: The rising cost of resources and global indicators of change. American Scientist **103**, 6 (2015)
20. King, C.W.: Information theory to assess relations between energy and structure of the u.s. economy over time. BioPhysical Economics and Resource Quality **1**(2), 10 (2016). https://doi.org/10.1007/s41247-016-0011-y.
21. King, C.W., Maxwell, J.P., Donovan, A.: Comparing world economic and net energy metrics, part 2: Total economy expenditure perspective. Energies **8**(11), 12,347 (2015). https://doi.org/10.3390/en81112347. http://www.mdpi.com/1996-1073/8/11/12347
22. Lane, R.E.: The Loss of Happiness in Market Democracies. Yale University Press (2000)
23. Mazzucato, M.: The Value of Everything Making and Taking in the Global Economy. Public Affairs, New York (2018)
24. Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W.I.: Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books, New York (1972)
25. Mirowski, P.: More Heat than Light: Economics as Social Physics, Physics as Nature's Economics. Cambridge University Press, Cambridge (1989)
26. Sautoy, M.D.: The Great Unknown: Seven Journeys to the Frontiers of Science. Penguin Press, New York (2016)
27. Simon, J.L.: The Ultimate Resource 2, revised edn. Princeton University Press, Princeton, N.J (1996)
28. Smil, V.: Energy in Nature and Society: General Energetics of Complex Systems. The MIT Press, Cambridge, Mass. (2008)
29. Stern, D.I., Kander, A.: The role of energy in the industrial revolution and modern economic growth. The Energy Journal **33** (2012). https://doi.org/10.5547/01956574.33.3.5
30. Turchin, P., Nefedov, S.A.: Secular Cycles. Princeton University Press (2009)