Chapter 6
Macromodel on the Wall, How Does Growth Occur, After All?

> "Everything should be as simple as it can be, but not simpler"—Albert Einstein[1]

> You can resolve not to do the work of power for it. You can resolve not to let lies be told in your hearing. You can resolve not to use sloppy language that is euphemism.[2]—Christopher Hitchens (2002)

What are Models, and Why do We Use Them?

A model is a greatly simplified interpretation of a complex thing. A model on the cover of *Cosmopolitan* magazine is one (usually attractive) example of the human form (in fancy clothes). A toy car is a model, or simplified and shrunken representation, of an actual car.

This chapter is not about these types of models. Rather, this chapter describes economic models that are mathematical equations (without actually showing the equations!) used to both describe patterns in historical data and project possible future outcomes. Chapter 5 quoted ecologist Howard T. Odum as he stated that it might not be possible for a system to understand itself, but it can try. This means that since we reside within our economy, we might not be able to fully explain the economy, but we can try by developing "…simplified ideas …called models …which have enough of the main features to have some reality but are simple enough to be understood."[3] That is what this chapter is about. In particular this

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[1] Roger Sessions, 1950 January 8, How a 'Difficult' Composer Gets That Way by Roger Sessions, Page 89, New York. (ProQuest) and discussed at http://quoteinvestigator.com/2011/05/13/einstein-simple/.

[2] Speech at The Commonwealth Club, "Why Orwell Matters," October 21, 2002. Viewed at https://www.youtube.com/watch?v=rY5Ste5xRAA&t=1923s.

[3] Odum [52, p. 119].

C. W. King, *The Economic Superorganism*,
https://doi.org/10.1007/978-3-030-50295-9_6

chapter focuses on economic models that explain macro-scale phenomena such as GDP, total primary energy consumption, and population.

This type of modeling is in many ways the exact opposite of modeling clothing. Equations are objective. There is nothing subjective about an equation. We invented mathematics in order to be as objective as possible for counting objects and describing regularities in the physical world.

However, there is one very important commonality between mathematical models and models on the pages of *Cosmopolitan* magazine: each model influences our perception of the real world.

A model represents some aspect of the real world, but it cannot represent the totality of the real world. Many critiques of fashion models describe them as disproportionately young and exceptionally thin to the point of being unhealthy.[4] Some people are skinny, and some are voluptuous. Some people are tall, and some are short. People have different hair, eye, and skin color. Thus, the fashion model critique states that the composition of fashion models does not represent the variety of shapes, sizes, colors, and races of the real-world population.

Mathematical economic models face a similar problem. One mathematical model of the economy cannot represent the diversity of countries and phenomena we observe in the real world. However, some models more accurately describe data or make successful predictions than others, and most models are useful in their proper context. One of the most common quotes in this regard is from George Box and Norman Draper (usually only the first and second sentences):

> …all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind.—George E.P. Box and Norman R. Draper (1987)[5]

The challenge of using mathematical models composed of equations is that one needs a framework, a theory, or dare we say a narrative that forms the basis of creating the mathematical model. This was nicely stated by George Backus who spent much of his career making complex mathematical models of the economy:

> …a narrative is a metaphor, whereas an "equal sign" mathematical statement is precise, that unequivocally states the meaning and use of a number. It may be wrong, but is easy to critically evaluate.[6]—George Backus (2017)

The items on the left side of an "equal sign" represent *exactly* the same quantity as the items on the right side: $2 + 2 = 1 + 3$. By "easy to critically evaluate" Backus means that if you put your mind to it, you can test if the items on one side of the equation do indeed equal the items on the other side. The first law of

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[4] Kirstie Clements, July 5, 2013, *The Guardian* "Former Vogue editor: The truth about size zero": https://www.theguardian.com/fashion/2013/jul/05/vogue-truth-size-zero-kirstie-clements. Valeriya Safronova, Joanna Nikas and Natalia V. Osipova, September 5, 2017, *New York Times*, "What It's Truly Like to Be a Fashion Model": https://www.nytimes.com/2017/09/05/fashion/models-racism-sexual-harassment-body-issues-new-york-fashion-week.html.

[5] Box and Norman [8, p. 424].

[6] Personal correspondence.

thermodynamics was first a concept that the energy content of a system *before* some physical process takes place (i.e., items on the left side of the equation) is exactly the same *after* that process occurs (i.e., items on the right side of the equation). This concept has been tested and confirmed so many times that it became physical law.

While scientists and engineers are convinced of the usefulness of the laws of physics in their work, it is exceedingly difficult to sway public opinion by describing equations. When Stephen Hawking wrote his best-selling *A Brief History of Time* he was told that every equation in his book would reduce sales by half.[7] Apparently Hawking took the advice to heart: his book has only one equation.

Whether one understands the mathematics behind physical laws or not, we all inherently follow them. I don't have to understand gravity and friction to walk along the sidewalk, and I don't have to understand how an airplane works to ride in it. However, if I want to design an aircraft, I do need to understand how it works. Our lives literally reside in the minds of engineers and scientists when they use mathematical models to design our cars, planes, and bridges. People can die if the equations are wrong.

The same concept holds for economists modeling the economy. While our lives might not immediately and directly be in the balance, we trust economists to use accurate models to design rules for our economy.

> While a poorly designed economic model, say, used to design a tax policy, might not directly lead to human death, the underlying economic principles certainly indirectly affect the distribution of resources and thus human well-being.

The problem is that economists often use models in ways that aren't accurate, aren't consistent with data, and don't actually describe how the economy works. A quote from 2018 Nobel Laureate Paul Romer's 2016 diatribe, *The Trouble With Macroeconomics*, sums this up nicely:

> The trouble is not so much that macroeconomists say things that are inconsistent with the facts. The real trouble is that other economists do not care that the macroeconomists do not care about the facts. An indifferent tolerance of obvious error is even more corrosive to science than committed advocacy of error.[8]—Paul Romer (2016)

Other economists have taken a more measured approach to critiques of flawed economic theories:

> Macroeconomists should pause before continuing to do applied work with no sound foundation and dedicate some time to studying other approaches to value, distribution, employment, growth, technical progress, etc., in order to understand which questions can legitimately be posed to the empirical aggregate data.[9]—Jesus Felipe and John McCombie (2006)

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[7] Martin Gardner, June 16, 1988, *The New York Review of Books*, The Ultimate Turtle, https://www.nybooks.com/articles/1988/06/16/the-ultimate-turtle/.

[8] Paul Romer, The Trouble With Macroeconomics, September 14, 2016, https://paulromer.net/the-trouble-with-macro/WP-Trouble.pdf.

[9] Felipe and McCombie [12, p. 296].

In any case, both critiques leave little room for nuance: “do not care about the facts,” “obvious error,” and “no sound foundation.” I wrote this book because I very much think macroeconomists and scientists should care about the facts.

Narratives are supported on the backs of public opinion, which can be molded by theories supported by mathematical models (Chap. 9 discusses the shaping of public opinion in more detail). This is true for science and economics. Even when new data and science correctly contradict existing narratives and models, it can take a long time to overcome them. Incorrect models can allow incorrect narratives to remain pervasive even when more accurate models exist.

The purpose of this chapter is to explore critiques of mainstream economic models, specifically neoclassical economic theory, that do not sufficiently reflect the patterns we observe in the real world. I specifically focus on patterns related to energy consumption, energy efficiency, and economic growth. Per the quote of Felipe and McCombie, the chapter also discusses alternative models that include a more accurate, practical, and realistic description of the energy input needs to operate and grow the economy. These latter models represent examples that need to become as pervasive as what practically every economics student is taught in universities: neoclassical economics.

When it comes to understanding the role of energy in the economy, we don’t have to throw away neoclassical economic theory if it works. It just turns out that it doesn’t work very well. As this chapter explains, when we model economic growth without some unnecessary assumptions of neoclassical economics, and we include assumptions that constrain economic activity based upon known physical principles, like the laws of thermodynamics, we can much more informatively explain modern economic trends including the GDP and energy consumption patterns of Chap. 2 and the debt and wage patterns of Chap. 4.

Neoclassical Economics: The King of Economic Narratives

> Why had so much conventional wisdom been bullshit?[10]—Michael Lewis (2017)

The “mainstream” economic framework is called neoclassical economics. Because most economics faculty focus on teaching this theory to their students, the numbers of economists using this theory, and thus interpreting the economy under its worldview, far outweighs those using other worldviews. And make no doubt, *because of its inherent assumptions, neoclassical economics, like any theory, imposes a worldview.* Unfortunately, the vast majority of citizens and many economic practitioners do not know this worldview.

As introduced in Chap. 1, economic theory informs policy, and policy affects social outcomes via the distribution of money. Neoclassical theory is the framework for most policy, and most people don’t know this. However, American and European

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[10] *The Undoing Project: A Friendship That Changed Our Minds*, [39, p. 51].

citizens do know their situation, and many of them are disillusioned with politicians' and economists' explanations for the economic outcomes since the 1970s, including the 2008 financial crisis and 40-plus years of wage stagnation. Neoclassical economists didn't even have a quick answer for the Queen of the United Kingdom, Elizabeth II, when she asked of the global financial crisis, "Why did nobody notice it?"[11]

Because the vast majority of people don't contemplate economic theory, they don't understand that much of their disillusionment starts with neoclassical economics. This is why *neoclassical economics is perhaps the king of economic narratives*.

There are many critiques of neoclassical theory. Here I use information from only a subset of these previous writings.[12] This section provides a short history of how, from the beginning, neoclassical economics attempted to copy physics to justify itself as a rigorous *social science*. Unfortunately, those developing the theory did not fully incorporate what is known about the first and second laws of thermodynamics that tell us all energy is conserved in any physical process, but only some of that energy can perform useful work in the economy. In presenting a short summary of this issue, I lean on Philip Mirowski's 1989 detailed treatise *More Heat than Light*, and readers wishing to dive into more details should consult that book [46]. For readers that wish for mathematics and theoretical arguments about economic modeling in the consideration of laws of thermodynamics, see Nicholas Georgescu-Roegen's 1971 book *The Entropy Law and the Economic Process* [18].

Neoclassical Economic Narrative: Consumer Utility as Potential Energy

Chapter 2 summarized some history of originating the concept of energy, but it did not mention the idea of the *field* that separates the concept of energy from matter. The field, like energy itself, is a mathematical concept, a model if you will, that is useful. It was put into prominence by renowned scientist James Clerk Maxwell in the 1800s. His research led to our coupled description of the concepts of light, electricity, and magnetism. Thus, we speak not only of electric and magnetic fields, but of changing electromagnetic fields that emit radiation such as light and heat.

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[11] Andrew Pierce, "The Queen asks why no one saw the credit crunch coming," *UK Telegraph*, November 5, 2008 at: https://www.telegraph.co.uk/news/uknews/theroyalfamily/3386353/The-Queen-asks-why-no-one-saw-the-credit-crunch-coming.html.

[12] For the reader interested in a more thorough discussion of problems with neoclassical theory, see Steve Keen's *Debunking Economics* for one of the more extensive critiques, Charles Hall and Kent Klitgaard's *Energy and the Wealth of Nations* that includes discussion of energy-related issues, and Philip Mirowski's *More Heat than Light* that provides the historical background on how neoclassical theory was derived to mimic only part of what was known from classical physics in the 1800s [22, 30, 46].

Electricity, magnetism, and light are fully coupled phenomena. For example, if you affect the flow of electricity, you inherently change the corresponding magnetic field.

Understanding the concept of the field is important for understanding the foundation of neoclassical economics. Consider the gravitational field around large masses, such as planets. It is a *potential energy* field. Living on Earth, we all have experience with the effect of a gravitational field. For us, this field is static, meaning it does not change. The gravity you experience today is what you experienced yesterday. However, if you change the *boundary conditions* of a gravity field, then it changes.

The gravity you experience on the surface of a planet is defined by its size and mass. For example, the moon is less massive than Earth. When astronauts landed on the moon, they experienced a different gravitational field than they experience on Earth. Our weight is defined both by our mass and that of the planet on which we reside. The astronauts had the same mass on the moon, but less weight. This is because our weight is defined by the gravitational field within which we reside, and the field within which the astronauts temporarily resided was defined by the boundary condition, or mass, of the moon, not Earth. Here is the point to keep in mind: boundary conditions can change, and changing boundary conditions means potential energy fields change. When we describe how neoclassical economists use the metaphor of the potential energy field, we see their assumptions break down. They become inconsistent. For now, a bit more on gravity.

You are riding a bicycle (on Earth). If you ride along a flat surface, it is pretty easy. If you ride uphill, it is much harder because you must work against the *force* of gravity. In physics, force and a potential energy field are connected via geometry. If you move along a field line, from a lower to a higher potential, you must overcome an opposing force. The energy you must use equals the force times the distance you travel against that force. However, if you move *perpendicular* to a field line, you move from one point to another at the same potential. No force is required to move from a point with one potential to another point at the same potential where all points in between are also at the same potential. This is why riding a bicycle on a flat surface is not (as) tiring: you move perpendicular to the gravity field lines, and you are always at the same potential. You still have to overcome friction and wind resistance, but those are additional forces other than gravity (recall from Chap. 2 there are many types of energy).

Combine the idea of moving within a potential energy field with the idea of kinetic energy discussed in Chap. 2, and we're ready to understand the basic construction of neoclassical economics. To describe the total mechanical energy of an object we must add its potential and kinetic energies. When you coast on your bicycle increasingly faster down a hill you are losing gravitational potential energy and gaining kinetic energy in two forms: you and your bicycle moving with some speed in a single direction, plus the rotational energy of your bicycle wheels. (This is the same two kinds of kinetic energy as in the rolling billiard ball example of Chap. 2. The ball moves across the table—linear kinetic energy—and rolls—rotational kinetic energy.)

Neoclassical economists mimicked physicists' energy field concept from the 1800s. They replace potential energy with a concept of value they call *utility*.[13] The concept of utility comes specifically from that of the potential energy field. Each one of us is supposed to have our own utility field that describes the preferences of what we want to buy as consumers. Our preferences are expressed, or measured, by the quantity of each commodity that we purchase. The amount of each commodity we buy is the same concept of having a position in a potential energy field, so goes the concept. Thus, prices are the same as forces in potential energy fields, and markets are mechanisms to calculate prices.

If all forces on a particle within a potential energy field balance against each other, the particle is said to rest at an *equilibrium* position defined by the fact that all nearby positions have a higher potential energy. Another way of saying this is that balls do not roll uphill; they roll downhill, to positions of lower potential energy.

To neoclassicals, the "market" is at "equilibrium" when all consumers have purchased a quantity of each product at prices at which all producers are willing to sell. The theoretical place this occurs is a massive bazaar where all people exchange all products via barter transactions (e.g., 3 apples equal two pears, one pair of shoes equals 10 apples, etc.). A barter economy is one in which goods are exchanged for other goods. This exchange of items occurs such that the relative prices are determined and assumed to balance. Further, prices and quantities are determined simultaneously. If people purchase fewer apples, the price of apples goes up. If the price of pears goes down, people purchase more pears. Equilibrium is defined as the situation in which no different exchange of products can occur without making someone's utility lower. In this way, neoclassicals translated the physical concept of an equilibrium at a minimum in potential energy to an economic concept of equilibrium at a maximum in utility.

Note there is *no* fundamental underlying price. The prices of which neoclassicals speak are not specifically money per quantity (e.g., dollars per gallon of gasoline)

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[13] For the translations of potential energy to neoclassical economics, see Irving Fisher's 1926 *Mathematical Investigations into the Theory of Value and Prices* or Table 5.1 in [46] that is a reproduction. In physics, the potential energy field has a particular mathematical definition. Again, energy is a concept that is useful for understanding the physical world. In particular a potential energy vector field is defined by a mathematical integral. The vector field is derived by taking the derivative of a scalar field potential function. It has the property that if you move around within the vector field but return to the same point at which you started, there is no change in potential energy. Mathematically the term for this property is a "conservative vector field" that is "integrable." While neoclassical theory uses this integrability concept to solve for prices and demand at equilibrium, Wade Hands (1993) discusses [61], and Mirowski (1993) agrees [47], they do not directly translate the same mathematics as in physics. See Hands (1993) for discussion of how neoclassical theory uses mathematics consistent with the concept of a "conservative vector field." This is done by considering a consumer's budget constraint (e.g., how much can you buy with $100). By mathematically asking to (1) maximize utility with a budget constraint or (2) minimize spending to purchase a given set of items, neoclassical theory forms the Slutsky matrix that relates changes in quantities to changes in prices for a "scalar expenditure function" with equivalent mathematics of a Jacobian matrix that relates how changes in positions relate to changes in forces for a "scalar potential (energy) function."

that you see when you actually purchase something. The prices are relative: "how much of this is equal to one of those." This is not a fundamental problem to understand economic exchange. Everything could be "priced" in any single currency, such as cowry shells, gold, or apples instead of dollars. However, in a few paragraphs we'll learn how a problem arises when there is no explicit consideration of money as debt.

Also, "the market" determines prices without any specification of how much *time* it takes for producers to *supply* a certain number of items that consumers *demand* at equilibrium prices. That is, the consumer actually doesn't know how much she demands until she knows the price, but the price is not determined until the seller knows how much the consumer demands and then determines how much to produce. Mathematically this is not a problem. One can equate all demands on one side of an equation to all supplies on the other side and define the prices as those required to make to the equality true. That is what it means to come to economic *equilibrium*.

Using the metaphor of utility as potential energy can be helpful for understanding prices and how much people buy, but time doesn't appear in neoclassical theory because it uses *only* potential energy as a metaphor.[14] It might be justifiable to adopt the analog of the conservation of energy while neglecting the analog of kinetic energy, but it leaves important concepts and data unexplained.

In physics, if you neglect kinetic energy, you ignore mass and time. Recall that to calculate kinetic energy, you need to know mass and speed. No mass, no kinetic energy. No speed, no kinetic energy. If you only have 5 min to ride your bicycle home for dinner from your friend's house that lives down the perfectly flat road from you, you need to know how fast you have to ride, and thus, the kinetic energy you need to maintain. Your potential energy doesn't change from his house to yours, and thus potential energy can't tell you anything about how long it takes to get home.

In neoclassical economics, expenditures, or spending, is the corresponding concept to kinetic energy. Thus, the conserved quantity for neoclassical economics should be expenditure plus utility, just like the conserved quantity for (classical) physics is kinetic energy plus potential energy. Just like you need to know how fast you have to ride your bike to get home in 5 min, you need to know how much money you have to spend to install 100 MW of solar panels in 1 month. If you don't spend enough per day to hire enough installers, you won't get the full installation completed in time. Everybody has heard the old adage "time is money." It sounds better than "kinetic energy is expenditures."

While solving mathematically for economic equilibrium can be a reasonable concept to think about, I now emphasize three particular problems with the neoclassical approach that prevent it from providing enough explanatory power for the energy and economic trends and systems concepts discussed in the previous chapters.

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[14] This story of neoclassical economics improperly mimicking mechanical energy, or Hamiltonian mechanics, is the subject of Chapter 5 in [46]. Also see Section 4 of [47].

First, as already mentioned, there is no role for time. Everything happens over some unspecified time to come to equilibrium, or agreement on prices and quantities. Because there is no time, it becomes almost impossible to discuss an energy *transition*, where we use the term transition to imply change over time.

> How can we use neoclassical theory to inform the energy narratives without explicit consideration of time? We can't.

Because there is no time, there are no inventories of products that need to buffer imbalances between when people buy and when producers manufacture. Everything that is produced is sold. As Mirowski states: "Transactors were not allowed to hold stocks of inventories except for personal consumption; transactors were lobotomized into passively accepting a single price in a market ..."[15] This lack of inventory would be like all consumers and producers first meeting at an empty grocery store, then coming to an agreement on prices and quantities for steaks, lettuce, and cheese, and finally with a head nod (as in the 1960s sitcom *I Dream of Genie*) or an eye twinkle (as in the competing 1960s sitcom *Bewitched*), all of the food shows up in the correct quantities of each shopper's cart. Somehow everyone's cart is full of groceries yet the grocery store itself never actually contains any food, and we don't know how long it takes for this process to happen. This lack of inventory sounds a little odd because we go to the grocery store specifically because it is a building that stores food.

Second, even though neoclassicals recognize that money exists, to them the quantity of money itself does not affect anything in the economy. The three commonly stated properties of money are as a medium of exchange, a measure of value, and a store of value. For money to act as a medium of exchange means that people give money to buy any good or service and receive money if they produce a good or service. To some this means that money exists to avoid operating a barter economy in which people must exchange one set of goods for another set of goods. However, there has never been an economy based solely on barter.[16] The reason, as discussed in Chap. 4, is that most pre-industrial transactions were among people that knew each other and encountered each other on a regular basis. Economic participants neither had to instantaneously exchange good-for-good, nor use money. They could understand that each had an obligation, or form of debt, to have a one-way exchange today and wait for a reciprocal exchange some time in the future. Because neoclassical economics does not fundamentally consider time, it is easy to see why the theory associates money as needed only for instantaneous exchange. Also, if there is no time (or memory or future), then each person you meet is effectively a stranger since you can't remember meeting them in some past that didn't exist. We can wonder if the lack of time and debt in economic analyses helps transform us into strangers.

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[15] Mirowski [46, p. 240].

[16] A good reference is Chapter 2 "The Myth of Barter" of David Graeber's *Debt: The First 5000 Years* [20], in particular page 29 for a quick synopsis.

Not only does this simplified view of money avoid a historical bogeyman of the barter economy, but it also avoids describing the real-world influence of money in our modern economy. If there is no role for the *quantity* of money to affect anything, the concept of borrowing money as debt or a loan also does not exist. Thus, the concept of money is assumed, but money performs no fundamental role in the economy. If your theory can't consider time along with money as debt, then you can't consider concepts like paying interest, over a period of *time*, on loans for homes, cars, and university expenses. A quote from Steve Keen summarizes the problem:

> It may astonish non-economists to learn that conventionally trained economists ignore the role of credit and private debt in the economy—and frankly, it is astonishing. But it is the truth. Even today, only a handful of the most rebellious mainstream 'neoclassical' economists—people like Joe Stiglitz and Paul Krugman—pay any attention to the role of private debt in the economy, and even they do so from the perspective of an economic theory in which money and debt play no intrinsic role. An economic theory that ignores the role of money and debt in a market economy cannot possibly make sense of the complex, monetary credit-based economy in which we live. Yet that is the theory that has dominated economics for the last half-century. If the market economy is to have a future, this widely believed but inherently delusional model has to be jettisoned.[17]—Steve Keen (2011)

Finally, there is no role for how much it costs to produce something. There are only prices, no costs. For neoclassicals, price is not a function of how much it costs to produce something. It is solely a function of the consumer demand and producer supply curves determined during exchange of all goods and services. The producers *have to sell* everything they produce and the consumers *have to buy* everything produced at the equilibrium prices determined at some unspecified time. Want 1000 apples? The price is equal to an ounce of cheese. Want only 1 apple? The price is equal to one pound of cheese. To neoclassicals it doesn't matter how much it costs to make cheese. Of course, there are costs to making cheese. A cheese maker pays for milk from a cow that requires feed and water to keep alive. It takes time and physical resources, such as energy, to raise a calf, make cheese, grow apples, make airplanes, transport plastic toys from China, etc.

With all of these assumptions and caveats associated with using neoclassical theory, it is amazing that it is so widely practiced. This is precisely why neoclassical economics is the king of economic narratives.

Real businesses make goods, borrow money to pay for real costs, and use inventories to account for discrepancies in timing between sales and production. It is up to each one of us to decide how to appropriately use any economic model that does or does not account for time, costs, debt, inventories, and any other physical or social concept. To further understand the concepts of the cost of production, we now turn to the neoclassical theory model of economic growth, or production.

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[17] Keen [30, p. 6].

Neoclassical Economic Narrative: Production and Growth

Economists use the term *production* to mean the act of creating goods and services. More production is akin to higher GDP. But just how does production occur? What does it take to produce something? Mirowski notes that there is no greater "…source of discord in the history of neoclassical theory …" than that due to lack of consensus concerning the meaning of production.[18] "Production … does not "fit" in neoclassical value theory."[19] For a more entertaining quote:

> To get a trained economist to entertain this thesis [that production is not conceptually consistent with neoclassical value theory] is as easy as getting a Catholic priest to entertain the notion of the fallibility of the Pope.[20]—Philip Mirowski (1989)

The reason is that neoclassical economists are wedded to the idea of the potential field, as discussed in the previous section, to describe the value of purchased economic output. In effect, they try to use it to imply how the economy produces goods and services, but their method doesn't work conceptually or in practice.

Because neoclassicals assume that value, or utility, derives from consumers and producers at the moment of exchange, when prices are determined, there is no role for the *time and cost* of production to affect the value of goods. That is to say, because it doesn't matter how much it costs to produce a good, the ultimate value has nothing to do with that history. As economist Nicholas Georgescu-Roegen noted:

> The Neoclassical mode of representing the production function ignores the time factor.[21]—Nicholas Georgescu-Roegen (1971)

The lack of sufficient history stems from the lack of the concept of time that it takes to move from one equilibrium (of supply and demand) to another. This is the outcome of using a potential field theory to establish economic value. A static field has no history, no arrow of time that we experience by remembering events that happened in the past, or how much time it takes to go from "here to there. " In the simplest terms, goods available for you to buy "now" had to be produced in the past, or before "now," but to neoclassicals these factual historical events of production don't matter.

There is a good point to the neoclassical argument that prices of goods are determined when people buy them. We've all seen the price of a dress drop dramatically when going "on sale." Clearly the price of a dress can and often does have little to do with its cost to produce. Also, in developing countries there are often localized markets, say in the center of the city, where sellers congregate in one location, selling various goods from their booths. In these markets it is quite normal for sellers and consumers to haggle "on the spot" over the price of shoes,

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[18] Mirowski [46, p. 293–294].

[19] Mirowski [46, p. 284].

[20] [46, p. 284].

[21] Georgescu-Roegen [18, p. 244–248].

kitchen wares, and clothes. In these cases the price really is determined at the end of a negotiation, but there are lower bounds.

It is possible, or course, for a business to produce a good that no one wants to buy. If this business only produces this good that no one buys, it will go bankrupt. Why? Because it costs more than zero dollars and zero energy to produce anything. At a minimum the business owner has to pay for his food to stay alive and the raw materials for his product even if he makes it by hand. If it costs one dollar to make a product, but consumers will only pay fifty cents for it, the business will eventually go bankrupt and the good will cease to exist.

When I was in college there was a convenience stand within the mechanical engineering building selling snacks and some donuts. Students being poor, and engineers taught to be resourceful, we noticed that at closing time the workers would put the vendor's unsold donuts into the trash can in the hallway. Not being biology majors, we figured that free donuts in the trash for less than 15 min were no less healthy than fifty-cent donuts in the display case 15 min earlier. We didn't stop eating donuts, but we stopped buying donuts, at least for a while. The vendor shut down and didn't return to the building the following semester.

In neoclassical theory, this reality of supply-demand mismatch does not exist because the exact quantity consumers are willing to buy to maximize their utility comes into existence irrespective of time or cost. The donut vendor didn't keep lowering prices until we bought all of the donuts, thus making supply equal demand. We didn't have a discussion with the business owner to come to an agreement on donut prices. Her supply at stated price was greater than our demand at that price, and she threw away the remaining donuts, which we then ate for free.

But enough about donuts. This book is about energy. How do neoclassical economists model how to "produce" something, and in particular how do they include the concept of energy?

Let's explain neoclassical economic production by using a standard introductory textbook, *Macroeconomics* by Paul Samuelson (Nobel Prize in Economics, 1970) and William Nordhaus (Nobel Prize in Economics, 2018) [56].[22] The book mentions economic production has four types of inputs: human resources (labor supply, education, discipline, motivation), capital formation (machines, factories, roads), natural resources (land, minerals, fuels, environmental quality), and technology (science, engineering, management, entrepreneurship). These factors combine into an *aggregate production function* relating economic net output, or GDP, to the amounts of these input *factors of growth*.

We can imagine people (the labor, educated to some extent) working in a factory or office building with machines (capital) that require fuel and raw material (natural resources) inputs with which to operate machines and make new products. The explanation of natural resources notes important resources are arable land and soil, oil and gas, forests, water, and mineral resources. This all sounds reasonable, but it goes downhill from here.

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[22] Samuelson and Nordhaus [56, p. 217–231].

The *Macroeconomics* authors start simplifying. They appropriately refer to Robert Solow as an "apostle" and the father who birthed the mainstream neoclassical growth model from his head in 1956 [57]. For his work, Solow received the Nobel Prize for Economics in 1987, and to his credit he recognized, even at the time of originating the model, that his framework neglected to explain a large portion of economic growth, often attributed to "technology," as will be described shortly [58].

However, the first step Samuelson's and Nordhaus's text takes in describing Solow's model (also known as the Solow–Swan model) is to remove natural resources from the equation. This will turn out to be a big problem. It is important to note that at the time of his original work in the 1950s, Solow included the amount of natural resources (via its economic value) in the concept of capital. However, this is still not equivalent to considering energy consumption as fuel for machines. In agrarian times no one debated that land was needed to produce food and fodder. In the fossil-fueled industrial era, land was no longer a limiting input for growth. But total energy and physical natural resource flows have always been relevant for economic activity.

For now, consider the equation for growth of GDP has only three inputs: capital, labor, and "technology."[23] This production function concept now treats "technology" as another potential field, just like the one governing consumer utility. This is not obvious. Just like you define your supposed utility potential field via the combination of products you prefer, a technology potential field is defined by the quantity of input capital and labor needed to produce economic output. Recall that the mathematical concept of the potential field "…is useful only in cases where one can safely abstract away all considerations of process and the passage of time."[24] Just as there are many combinations of products you can buy to achieve your maximum utility, there are many combinations of capital and labor that can achieve a given level of economic output.

One important consequence of production as a potential field is that it cannot deal with the real concept of *intermediate inputs*, or those "…outputs that, directly or indirectly, become inputs of the same production process."[25] This is a problem when applied to energy and natural resources, because it means the theory can't conceptualize and use important feedback concepts such as energy returned on

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[23] The common form of the neoclassical production function is called the Cobb–Douglas production function. In the case of Solow's version, there are only two core inputs, and GDP is expressed as $Y = A(t)K^{\alpha}L^{(1-\alpha)}$ where $Y =$ GDP, K is the value of all capital (perhaps adjusted for quality of different types of capital), L is the hours worked by all workers (perhaps adjusted for different labor quality), α is the output elasticity of capital (and less than 1), $(1-\alpha)$ is the output elasticity of labor, and $A(t)$ is the "technological progress" function of time t, estimating what is known as *total factor productivity* to minimize the difference between the estimate from this equation and the GDP data [58]. The *Solow residual* is the difference between the data on economic growth and the estimate from this equation without $A(t)$, within α equal to the GDP cost share of capital, and $(1-\alpha)$ equal to the GDP cost share of labor.

[24] Mirowski [46, p. 347].

[25] Mirowski [46, p. 319].

energy invested, or how much energy it takes to extract and convert energy to fuels (refer back to Chap. 5). We know, from physical principles, that we have to consume some energy to build and maintain machines that in turn extract energy from the environment. By only modeling production using a field concept, with no other specifications, you can't figure out if energy extraction might become too expensive or physically limiting itself to enable economic growth, such as during the recessions of the late 1970s and 2008 financial crisis, when energy spending crossed a growth threshold near 8% of GDP (Fig. 2.13). Recall that major recessions have corresponded to times when a high percentage of GDP was spent on energy [5, 33].

After removing physical resources, the second step is to assume capital no longer need be described as distinct physical items that need fuel (energy) inputs to operate, but to assume capital is now the monetary value of the physical items. This problem, as well as that of defining technology as a field, was at the heart of what was known as the "Cambridge Capital (Theory) Controversies" (CCC) in the 1950s and 60s: a battle between economists in Cambridge, MA, United States versus those in Cambridge, United Kingdom. A group of U.S. economists, including Robert Solow and Paul Samuelson, at Massachusetts Institute of Technology (MIT) advocated for the neoclassical production theory, while another group of economists, including Joan Robinson and Piero Sraffa at the University of Cambridge, U.K. argued against it. The British argued that the process of economic production is grounded in physical processes that require various types of physical capital. Because different types of capital have fundamentally different properties (e.g., a building is different than a truck), you cannot combine them into one *aggregate* quantity of capital. Mathematically you cannot add items of different units, and this is essentially what one does when aggregating capital.

Most economists know that adding all types of machines together by their economic valuation is a simplification. One mainstream macroeconomics textbook states "…it should be clear that it is still a drastic simplification of reality. Surely, machines and office buildings play very different roles in production and should be treated as different inputs."[26] But is it a useful simplification? To some degree it can be, if you give up on the strict assumptions of neoclassical growth theory. As stated by Nicholas Georgescu-Roegen:

> As a highly abstract simile, the standard form of the Neoclassical production function—as a function of …homogeneous "capital," and …homogeneous "labor"—is not completely useless. But …the value of the standard form of the production function as a blueprint of reality is nil. It is absurd to hold on to it in practical applications—as is the case with the numberless attempts at deriving it from cross-section statistical data. …True, capital and labor may be rendered homogenous but only if they are measured in money.[27]—Nicholas Georgescu-Roegen

Pay attention to Georgescu-Roegen's statements that the concept of total aggregate (or homogeneous) capital is not "completely useless" if the quantity of capital is

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[26] Blanchard [6, p. 216].

[27] Georgescu-Roegen [18, p. 244].

"measured in money." The CCC was largely about whether it was useful to aggregate capital via its monetary values. However, even some steadfast adherents to modeling the physical nature of economic production accept the idea of aggregating capital, labor, and energy for the purposes of modeling economic output. For example, Reiner Kümmel and Dietmar Lindenberger state that just as you could use the input factors of capital, labor, and energy to uniquely describe physical work and information processing in their own right, you can also use those input factors to uniquely describe economic output in units of money [40].[28] However, there are physical constraints on how energy and capital relate to each other that must be considered at some level (to be discussed later).

The MIT contingent conceded on the philosophical conundrum of aggregating capital with physical qualities, but argued it was still acceptable to combine all forms of capital by adding their monetary values into an aggregate capital value that, in the end, still does not determine prices. Remember, neoclassical theory states that prices are determined by consumer preferences, not production costs. The U.K. Cambridge criticisms derive from neoclassicals forcing production into the mathematical framework of the potential energy field, although Mirowski states they never quite grasped this fundamental linkage to a principle of physics.[29] The field framework is simply not suited for the concept of production whose purpose is to describe how inputs are combined to create some output that is different in practically every way from the simple sum of the inputs.

Ultimately what comes out of the CCC is that the neoclassical paradigm won the war of practicality by instilling their economic growth model into the bulk of economists minds today.

Step three for the Solow model is to calculate aggregate labor in a similar manner as done for capital. Labor is now all hours worked by all types of people. Neoclassical economists recognize the fact that all types of capital and workers are not equal. When calculating the input factors of capital and labor they "adjust" for differences in quality. For example, a surgeon provides higher quality labor than say a construction laborer. However, this quality adjustment is performed on the basis of hourly pay, which neoclassical economists assume must be the correct pay based upon the value of that worker's *marginal* contribution to the economy as expressed by his equilibrium price for labor. In the phrase worker's marginal contribution, economists assume that each person gets paid based on the value they contribute to the economy.[30] However, neoclassicals still must translate this quality difference into the same units, such as hours worked. For example, a surgeon is tallied as

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[28] "Since work performance and information processing are subject to the causal laws of nature, their result, the economic output, should depend as uniquely on the work-performing and information-processing production factors capital, labor, and energy as any state function of physical systems depends on its physical variables." [40].

[29] Mirowski [46, p. 341–343].

[30] The economics terminology for a person being paid based on the value they contribute to the economy is "quality of labor adjustment represented by workers being remunerated according to their marginal productivity."

working more quality adjusted hours than a laborer even if they each work 8 h per day.[31]

Note what is inherently assumed by inserting quantities for aggregate capital (a sum of the quantities of all types of machines) and aggregate labor (a sum of all labor hours across all types of human work) into an equation. One assumption is that one type of capital can indeed perform the function of another type. This is like saying a refrigerator can make a solar panel or drill an oil well. Another assumption is that one type of worker can perform the function of another worker. This is like saying a construction worker can perform brain surgery, *successfully*, just by working longer. I suppose this is true, but only if he spent years acquiring the knowledge to become a surgeon. Only in the movie *The Matrix* can Neo plug into a computer network to acquire a lifetime of knowledge in a few seconds. Perhaps advances in artificial intelligence and understanding of our brain will enable *The Matrix* to become reality so that construction workers can take the red pill and perform surgery a few seconds later. For now, we can only speculate, and in Chap. 8 I will opine on how artificial intelligence and evolution might be consistent with neoclassical or other views of economic growth that more directly include energy within economic growth.

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[31] "Changes in labour quality reflect movements in the distribution of hours worked among categories of workers, and differentials in the hourly pay of categories of workers. For example, if hours worked by a highly skilled and highly remunerated type of labour (such as brain surgeons) increased, then the volume of labour input as measured by QALI [quality adjusted labor input] would increase by more than the observed increase in hours. Conversely, a decrease in hours worked by unskilled workers in elementary occupations who receive lower than average remuneration would result in a fall in QALI by less than the proportional decrease in hours worked." From "Quality adjusted labour input: UK estimates to 2014," Release date: 22 May 2015, https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/qualityadjustedlabourinput/estimatesto2014;

"We calculate QALI [quality adjusted labor input] by categorising workers by identifiable characteristics (based on age, sex, industry of employment and level of education), and weighting changes in the hours worked of each worker type by their share of total labour income. The rationale for this approach is that, under competitive markets, economic theory suggests that different factors of production (different categories of workers, and different types of capital assets) will be remunerated according to their marginal productivity. Consequently, relative shares of labour income provide a proxy for the relative productivity or "quality" of different types of workers.

Using a suitable weighting system, it is possible to subtract movements in hours (sometimes referred to as "unadjusted hours") from movements in QALI indices, and hence to identify the pure "quality" or compositional movement in labour input to production.

From the perspective of measuring productivity, it is the movement in QALI rather than the movement in hours worked that offers a better representation of what is happening to labour input. For example, growth in labour quality of 1% with hours unchanged is equivalent (abstracting from distributional effects) to growth in hours worked of 1%, with labour quality unchanged." From "Quality adjusted labour input: UK estimates to 2016," Release date: 6 October 2017, https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/qualityadjustedlabourinput/ukestimatesto2016.

Labor substitution could go the other direction, however. There might be an intellectually skilled person that chooses to perform low-skilled physical labor in construction. The movie *Office Space* portrayed exactly that as a computer programmer got fed up with his pointless job, which as far as he could tell, only existed to help his boss's stock go up a "quarter of a point." He did not feel that either he or his boss was getting paid based on what he felt was any real contribution to the economy. If you don't want to rely on movie fiction to demonstrate the fallacy that all people get paid based on the value they contribute to the economy, then consider the first two pages of David Graeber's book *Bullshit Jobs* [21]. There, Graeber recounts a story from a German worker employed by a subcontractor of a subcontractor of a subcontractor for the German military. A tremendous process ensues to move a computer from one office to another two doors down: "So instead of the soldier carrying his computer for five meters, two people drive for a combined 6–10 h, fill out around fifteen pages of paperwork, and waste a good four hundred euros of taxpayers' money."[32] Another common analogy to juxtapose the value of a job with its pay is a garbage collector; just try to imagine New York City if garbage collectors stop working for a week (as actually happened in 1968) as opposed to a 1 month strike of the city's public relations professionals.

We can now take the fourth and final step for understanding the limitations of the Solow growth model. Now that neoclassicals have removed resources from the growth equation, added up all of the physical machines and buildings of the world into a number for capital, and added up all of the different forms of work into a number for labor, they calculate the remaining input factor that describes GDP: *technology*. Except, we don't know what "technology" is. No problem. There are four parts of the economic growth equation: GDP on one side, and capital, labor, and technology on the other. We gather data to estimate GDP. Thus, the actual fourth step is to estimate technology growth as equal to the growth in GDP minus the growth in capital minus the growth in labor. Instead of leaving GDP on one side of the equation by itself, we can reshuffle the equation so that technology is on one side by itself. Economists call this measure of technology *total factor productivity*, or TFP.[33]

The important takeaway is that TFP is not itself defined by any first principles. It is by definition the *unexplained* part of economic growth when subtracting components assumed within the Solow model. TFP was originally called the "Solow residual," where *residual* is the mathematical term for the portion of the output of an equation that is not explained by the inputs of the equation. Thus, the Solow residual was the part of economic growth that remained unexplained after accounting for capital and labor. For this reason the Solow model is termed an

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[32] "Bullshit Jobs," LiquidLegends, https://www.liquidlegends.net/forum/general/460469-bullshit-jobs?page=3, written June 28, 2014, accessed January 21, 2019. Referenced in [21].

[33] Technological growth, or growth in total factor productivity (TFP), is mathematically the growth in GDP minus the *weighted* sum of the growth of labor and capital. Labor is usually weighted by about 65–75%, and capital is usually weighted the other 25–35%.

exogenous growth model, meaning that "technology" growth comes from outside the model. If you don't use the Solow model, you don't have TFP. In this way, TFP and the neoclassical exogenous growth model come together.

Mirowski sums up the unwelcome conclusion for using the neoclassical theory of production:

> Neoclassical economics shifted the onus of invariance [What is constant, my own preferences or the properties of the physical world?] onto individuals and their preferences, but in doing so neglected to elaborate the mechanism whereby the physical world retained its identity for the economic actor. Hence the possibility exists that the economic identity of goods may clash with their physical identity, with dire consequences for the theory of value.[34]

Yes, this means that neoclassical theory assumes people can agree to prices, and thus value goods, without any understanding of the required natural resources inputs or engineering processes that convert resources into those goods. Sure, consumers generally do not know the physics or engineering of how to make things. They don't have to know and generally do not care to know. But someone needs to know! Producers do need to know how to make things, at least at some basic level, and the producers that learn more about how to make things usually make the choice to make them with fewer inputs and/or increased functionality.

In short, neoclassical economic theory confuses people as to the role played by energy, other natural resources, and engineering constraints in producing goods. It does this by positing that "production" ultimately requires no explicit description of the physical world or relation to physical constraints. Therefore, if pricing influences how many goods one purchases and consumes, and human well-being is at least partially based on what we consume, then well-being also has no relation to the physical world.

Note what has now happened. Natural resources were originally stated as necessary inputs to produce goods. Then they were removed when it was time for economic calculations, and replaced with TFP. Economists replaced things we can count (land area, joules of energy, kilograms of materials) with a mathematical remainder called total factor productivity. Is this a big deal? Absolutely. For the U.S., estimates of TFP growth averaged near 1.3–1.6% per year in the twentieth century.[35] U.S. GDP growth averaged 3.2% per year from 1948–2017.[36] Thus, half of the growth in GDP is unexplained by a model that is supposed to explain economic growth! Economists do recognize that this TFP as technology is not a satisfactory concept, and Solow noted this when he initially derived the model.

Since the 1980s economic growth research has explored how *endogenous* technological progress can be characterized by capital and labor changes within

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[34] Mirowski [46, p. 322].

[35] Gordon [19, Figure 16–5].

[36] Data from U.S. Federal Reserve of St. Louis, Bureau of Economic Analysis data code A191RL1Q225SBEA, Real Gross Domestic Product, Percent Change from Preceding Period, Annual, Seasonally Adjusted Annual Rate.

the model [53]. However, the vast majority of this research focuses on developing *human capital* (education, know-how, and research and development capacity) within a country that lacks enough skilled workers. Thus, endogenous growth modeling still largely ignores the role of energy and natural resources in growth. Some energy-minded researchers have included the concept of endogenous growth by assuming "technological change" specifically refers to increases in the efficiency at which primary energy is converted into useful work [3, 10]. More of this research is a move in the right direction, but forcing it into frameworks that don't explicitly define resource stocks and flows might be a fool's errand. By construction, any economic framework that separates "technology improvement" from the use or definition of natural resources cannot describe how technology or the economy relates to interactions with the environment (e.g., to extract energy).

We now turn to explaining the implications from the lack of consideration of the principle of energy when modeling economic growth. This narrowed scope still requires explanation of several key points.[37] These points drove some researchers to more directly consider the role of energy in economic growth, and in doing so they created very important insights to more directly relate GDP to the use of energy.

The Energy, Stupid!

"The Economy, stupid," was a successful catchphrase used by James Carville, campaign strategist for Bill Clinton's 1992 U.S. presidential run. If you want to get elected in the U.S., talk about the economy. If you want to understand economic growth, you have to talk about energy. At least one book on the 2008 financial crisis makes this link to resources, using a variation of that quote as its subtitle: "It's the energy, stupid!" [49] Some researchers have taken this to heart.

Reiner Kümmel and Robert Ayres (along with Benjamin Warr) took similar minded approaches that have spawned a breed of energy-economic modelers to use their concepts for more accurate energy-economic modeling [3, 37]. As Ayres wrote with *Debunking Economics* author and economist Steve Keen, "[labor] without energy is a corpse, while capital without energy is a sculpture."[30, 32]

Saying it like that makes it simple. If we don't consume food, we die. If a machine doesn't use energy, it can't move. If an economic model does not include these concepts, then it should, because otherwise it has almost nothing to say about the role of energy in the economy. At the end of this chapter, I discuss insights from

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[37] One can read the following books for additional explanations of the fallacies of the neoclassical production function. Philip Mirowski's Chapter 6 of *More Heat than Light* details the theoretical problems [46]. Charles Hall and Kent Klitgaard point out some basic concepts in their 2018 *Energy and the Wealth of Nations* (Chapters 3 and 5) [22]. Blair Fix provides a nice summary of critiques of neoclassical production in his *Rethinking Economic Growth Theory from a Biophysical Perspective* [14].

my research that show taking these concepts to heart when modeling provides some important insights into important economic trends.

How could Kümmel and Ayres see past the fallacy of growth without energy? Perhaps because both Kümmel and Ayres are physicists. You can't get a physics degree if you ignore the necessary role of energy transformation to compute anything, move matter, or shape matter. Economic activity also involves these processes. Their education did not depend on accepting resource-free neoclassical theory as a description of the economy. Thus, when they thought about the economy, it was natural to include energy as a necessary input.

Neoclassical theory imposes some mathematical restrictions on production functions. They are not obvious to someone who simply reads a report discussing results from an economic model. However, it is crucial to understand these assumptions to then understand why neoclassical economists cannot interpret economic trends as being driven by energy. To explain this point we must discuss some math. But do not fear, dear reader, we will do this using words.

The Solow model is a variation of the more general Cobb–Douglas function (or equation form), which is in turn a variation on the even more general Constant Elasticity of Substitution (CES) function. We'll revisit CES functions later when we discuss modeling long-term changes to the energy system, such as transitioning to low-carbon energy. For now just consider that the Cobb–Douglas function lets you add as many input factors as you want into the growth equation.[38] Do you want to add energy consumption as an input? No problem. Neoclassical economists added total energy consumption into the Cobb–Douglas function. The result? Not much better than without energy. A lot of economic growth was still unexplained.

Here is where Reiner Kümmel comes in. At this point, he decided to model economic growth differently, by including constraints on how the three input factors, capital, labor, and energy, could relate to each other. He also used an even more general form of an economic growth equation than the Cobb–Douglas format—one that is still follows mathematical properties that neoclassical economists assume must hold for aggregate production functions [36, 37].[39] In doing so he could describe GDP such that the unexplained economic growth, or residual, was less than a few percent of the total—much less than the 50% attributable to TFP. But he also included changes that neoclassical theory doesn't. He allowed the output *elasticities*

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[38] The neoclassical Cobb–Douglas production function is of the generic form $Y = A(t)X_1^{\alpha_1}X_2^{\alpha_2}\ldots X_n^{\alpha_n}$ where $Y =$ GDP, each X_i is some input factor required for production, and $A(t)$ is the part of GDP not described by the input factors. Two other notable requirements to understand this Cobb–Douglas formulation are (1) that the sum of all of the exponents α_i must equal one and (2) the fraction of GDP paid to each of the input factors is equal to its respective exponent.

[39] This form he called the LinEx function, for "linear-exponential" function, in which economic output is a linear function of energy (or useful work, if desired) but an exponential function of labor, capital, and energy. The LinEx function contains technology parameters that may change in time (when creativity is active). They are to be determined econometrically by minimizing the sum of squared errors ("fitting") between the assumed equation and the data (e.g., GDP), subject to the constraints that each output elasticity is non-negative. See p. 199–206 of [37].

to change each year, based upon how capital, labor, and energy consumption change, rather than remain constant as assumed in the Cobb–Douglas function and Solow model. In economics, these elasticities relate how much economic output changes in relation to a change in one input factor.[40] Further, since he wasn't using the all neoclassical growth assumptions, his elasticities of the input factors are more flexible than those used in neoclassical theory, and via his formulation we can interpret the importance of each input in a different light. However, Kümmel's approach is generally ignored by economists. But just what are these elasticities supposed to be, and how do we make sense of them?

Each input factor in a Cobb-Douglas growth function is raised to a power, or exponent. To an economist, this exponent is the *output elasticity*, or the output elasticity with respect to the input. The sum of all elasticities must add up to one. This ensures that if you double *all* of the inputs into the economy, you get double the outputs, and this makes intuitive sense. Twice as many of the same exact machines with twice as much of each input can make twice as many of the same exact widgets. Since all elasticities sum to one, each elasticity is less than one. This means that there are "diminishing returns" from each input factor. For example, if you increase *only one* input factor by 10% and GDP grows by 5%, then if you increase that input factor an additional 10%, GDP might only grow by 4% more (some amount less than 5%).

For neoclassicals, the elasticity for each input factor is equal to the fraction of all input costs associated with that factor. These fractions of input costs to produce GDP are the so-called *cost shares*. The "cost share" theorem says that for any given input factor, its output elasticity is equal to the fraction of all input costs spent on that input factor. This equality "…is a consequence of the [neoclassical] assumption that the economy operates in an equilibrium determined by the maximization of either profit [or all of consumers' utility added up over infinite time]—without any constraints on input factor combinations." [38].

The neoclassical model, and the cost share assumption that inputs are paid the fraction of their contribution to GDP, breaks down for two main reasons. First, if there is no equilibrium, then prices, and thus cost shares, have not settled to their theoretically optimum level. If an input contributes a higher or lesser fraction to GDP than it is paid for that contribution, then this violates the cost share theorem. Data clearly show the economy is not in equilibrium as specified by neoclassical economics—the energy and economic data trends do not have constant rates of change. As we saw in Fig. 4.12, and will revisit in Fig. 6.6, the fraction of GDP paid to workers (or wages) has not remained constant over the last 50 years. Second, by constraining the elasticities to be equal to the input cost shares, the theorem constrains the inputs in the wrong way. We need to constrain how input factors of capital, labor, and energy relate to GDP, but in other ways. For instance, production

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[40] The elasticity of output, or GDP, with respect to an input, X is defined as the change in GDP divided by the change in X multiplied by the current value of X divided by the current GDP, or elasticity = $\frac{\partial GDP}{\partial X} \frac{X}{GDP}$.

functions need some representation of physical constraints, such as the fact that capital must operate both with energy as an input and never above 100% of its full capacity [32, 34, 40]. These types of physical constraints are missing in the Cobb–Douglas production function, thus the Solow growth model, and thus neoclassical growth theory. They must be added to represent physical laws and constraints, and when they are added in some way, you can no longer use the cost share theorem. *In short, the cost share assumption (and its assumption of equilibrium) of neoclassical theory is its fatal Achilles heel.*

Consider an example where energy, capital, and labor are the three input factors that create GDP. The post-World War II U.S. typically paid laborers 60% of GDP (Fig. 4.12) and household consumers spent about 7% (typically 5–10%) of GDP on energy (Fig. 2.9b). Thus, we must allocate the remaining 33% of GDP as profits to owners of capital such as stocks in companies, rental apartments, and other businesses. Per neoclassical theory applied to the Cobb–Douglas function, the growth in GDP *is equal* to 0.07 times the growth in energy consumption *plus* 0.60 times the growth in labor hours *plus* 0.33 times the growth in capital *plus* any residual factor.

The implications of this formulation are stark for understanding how neoclassical theory interprets the effect of energy on economic growth. For example, with an energy cost share of 7% "…a 99% fall in energy input would cause only a 28% fall in output [GDP]" if both capital and labor stay the same [32]. Over 70% of the economy can remain in operation with 99% of energy consumption gone? This result is absurd, as demonstrated by the following logical sequence. First, capital, or machines and buildings, consumes the vast majority of energy in a modern economy. Second, if left with only 1% of energy consumption, then all existing capital could only operate a very small fraction of its capability because it requires energy to operate. Third, therefore the economic value of all capital would plummet. Finally, as a consequence, GDP would further decline due to both reduced energy and active capital. Practically everyone, including neoclassical economists, recognizes this dynamic, but not everyone uses mathematics that is consistent with it. This is the crux of the problem.

We can gain insight into economic growth when using the production function concept with energy as an input factor, even assuming the Cobb–Douglas formulation. However, this must be done appropriately, i.e., by determining output elasticities without unnecessarily constraining them via the cost share theorem. When solving for the elasticities that provide a best match to the GDP data, *Kümmel and Lindenberger showed that economic growth is much more dependent on energy than normally believed by mainstream economists.* Their analysis shows that energy is an order of magnitude more influential than assumed when invoking the cost share theorem that implies a 1% reduction in energy consumption translates to only a 0.05–0.1% reduction in GDP [37, 40]. For example, from 1960–2013, a 1% change in energy translated (on average) to a 0.4% change in Germany's GDP and a 0.3% change in U.S.'s GDP [41].

Robert Ayres understood the value of Kümmel's concept. Like Kümmel, Ayres considers that energy must be an input into GDP, and it must be considered without the constraint of the cost share principle. But he adds a wrinkle. He takes into consideration the most fundamental energy-relevant machine characteristic that influences production: the *efficiency* at which a machine converts its fuel into useful work. In other words, he directly considers the second law of thermodynamics. Recall from Chap. 2 that useful work is the output from machines that consume fuels—the mechanical drive from a car engine or electric motor, the heat driving a chemical process, and the electricity powering computers and light bulbs. Useful work is equal to the energy delivered to a device times the efficiency at which that device converts that energy to its final form that performs some service.[41]

It makes perfect sense to consider *energy times efficiency*. To get more work out of physical processes we can consume more input energy *and* increase efficiency. Thus, Ayres and his former student Benjamin Warr set out estimating the efficiency of various processes. They multiplied energy that ends up in our cars, planes, buildings, and power plants by the respective efficiency of each to derive an aggregate total useful work for the entire economy. In this case of multiple processes that output useful work, it is entirely appropriate to aggregate them because they all have the same units of energy. When they divided all useful work by total primary energy for the U.S., they got an overall efficiency for the economy of about 4% in 1900 and 12% in 2000 (see Fig. 6.1). Most of the increase occurs from the 1930s to the 1970s. Shortly we will use this tremendous rise in efficiency to explain the neoclassical change in "technology" as total factor productivity (TFP).

In an attempt to communicate to neoclassical economists in language they understand, in one instance Ayres used the Cobb–Douglas production function with inputs of capital, labor, and useful work instead of capital, labor, and total energy [1]. When he did this, he effectively explained almost all of U.S. GDP without the need for a large residual factor like TFP. But the neoclassicals still can't accept Ayres' finding. Why? Ayres does keep each of his Cobb–Douglas powers constant, as a common simplification by neoclassicals, but he solves for the best power, or elasticity, to which each input is raised, rather than assuming the cost shares for each input factor per neoclassical theory. After all, there are no data to know the share of GDP that goes to purchase useful work. We don't pay for car motion and mechanical drive, we pay for cars and fuel.

At this point I've introduced researchers and methods that better explain historical GDP by incorporating the concept of energy and useful work, even through use of an aggregate production function that neoclassical economists use (but without one critical assumption). For some, this is enough to move forward with the useful work agenda. Others find that forcing useful work into aggregate production functions is like forcing a round peg into a square hole [23]. I conclude that if you are compelled to describe GDP with a single aggregate production function, then including the concept of energy or useful work, without the cost share assumption, is *much better* than neglecting energy flow altogether. We'll now discuss the length to which neoclassical economists go to explain the technological

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[41] Technically useful work is the exergy, not energy, delivered to a device times its efficiency. For this reason, some use the term "useful exergy" instead of useful work. Exergy is a measure of energy that accounts for the second law of thermodynamics. The exergy per kg of fossil fuels is only slightly lower than total energy per kg.

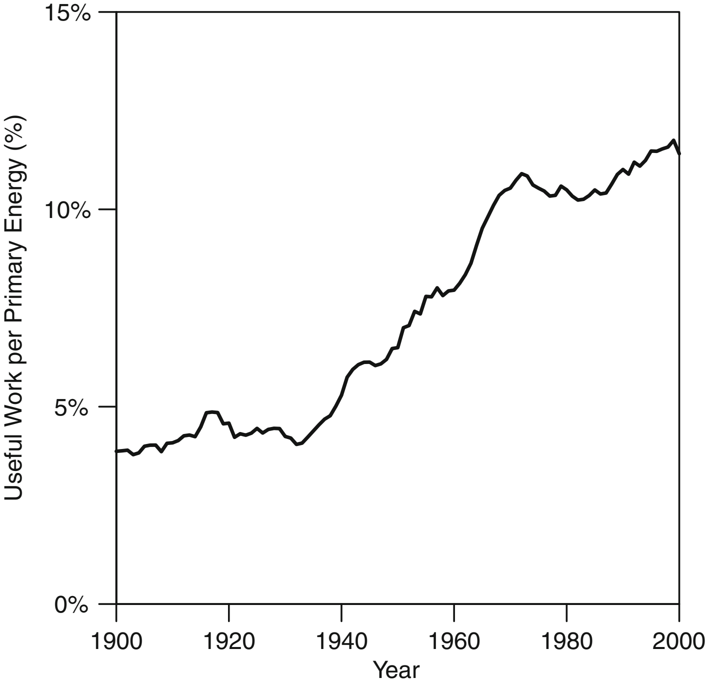

Fig. 6.1 The aggregate efficiency of the U.S. economy as useful work divided by primary energy consumption. Data from [62]

change without reference to energy. This is perhaps the most important reason why historical economic arguments produced more heat than light in trying to explain economic growth or technological change.

The Problem with Productivity: All Play and No Work

> Culture itself has become a commodity, and a combined force of economics and ideology now drives its dissemination, making retreat from the intercultural contact zones impossible and battles for control of the cultural environment a common occurrence.[42]—Bruce Wexler (2008)

In using the Solow neoclassical economic growth model that projects GDP using only capital, labor, and total factor productivity (TFP), adherents must spend a lot of time trying to explain TFP. Perhaps the most obvious trends to explain were the

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[42] Wexler [64, p.231].

tremendous economic growth rates during the three decades after World War II. Here is quote from a 2006 macroeconomics textbook by Olivier Blanchard [6]:

> The first two columns of Table 10-1 show growth rates of output per capita for both pre- and post-1973. Note that the growth rate fell in all four countries [France, Japan, United Kingdom, and United States]. Pinpointing the exact date of the decrease in growth is difficult. The date used to split the sample in the table was 1973, and this is as good as any date in the mid-1970s. ...
>
> At a growth rate of 4.1% per year—the average growth rate across our four countries from 1950 to 1973—it takes only 16 years for the standard of living to double. At a growth rate of 2.0% per year—the average from 1973–2000—it takes 35 years, more than twice as long.[43]—Olivier Blanchard (2006)

Blanchard is no slouch. He is a former Chief Economist at the International Monetary Fund. His book goes on to state three "facts about growth in rich countries since 1950." I list items one and three that are relevant for energy.[44]

> 1 Growth is not a historical necessity. There was little growth for most of human history, and in many countries today, growth remains elusive. Theories that explain growth in the OECD today must also be able to explain the absence of growth in the past, and its absence in much of Africa today.
>
> 3 Finally, in a longer historical perspective, it is not so much the lower growth since 1973 in the OECD that is unusual. More unusual is the earlier period [1950s and 1960s] of exceptionally fast growth. Finding the explanation for lower growth today may come from understanding what factors contributed to fast growth after World War II, and whether those factors have disappeared.

One only needs to look at the global data in Chap. 2, in particular Fig. 2.10, for which U.S. data show a similar trend, and note the same glaring anomaly in the growth rate of *energy consumption* in the 1950 and 1960s. Recall that 1955–1979 is the only time in history that the 10-year running average growth rate in energy consumption was greater than 4%/yr. Not only should every college economics student be exposed to these data of energy consumption and cost trends in Chap. 2, perhaps every high school student should learn them as part of a basic education. In explaining the high GDP growth rates of this period, the Blanchard text states (referring to neoclassical theory) "Our theory implies this fast growth may come from two sources ...," technical progress (i.e., TFP) and the growth of capital (per worker). So those are the *only* two sources to which neoclassicals look: better technology and more machines. In applying neoclassical theory to explain the GDP growth rates from the 1950s through 2000, the text states:[45]

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[43] Blanchard [6, p. 209].

[44] The text comes from the 2006, 4th Edition of Blanchard's *Macroeconomics* [6, p. 213]. The latest 2017 seventh edition has a similar, but different, discussion comparing rates of growth in select rich countries during the 1950–2011 period (Table 10-1) and noting rates of technological progress, or total factor productivity, and growth in output per worker since 1985 (Table 12-2).

[45] Blanchard [6, p.258–259].

1 The period of high growth of output per worker until the mid-1970s was due to rapid technological progress—not to unusually high capital accumulation.
2 The slowdown in growth of output per worker starting in the mid-1970s has come from a decrease in the rate of technological progress, not from unusually low capital accumulation.

Again, no discussion of energy extraction. Blanchard states that faster growth before the 1970s is due to a high growth rate of TFP, and slower growth after the 1970s is due to a low growth rate of TFP. In the earlier quote he states theories of growth "must ... be able to explain" the presence of growth in industrial rich countries and the absence of growth in the pre-industrial past.

A feasible answer for such a theory is apparent to someone who considers the physical and energetic basis of the economy. *The use of capital, which requires energy as an input, to more efficiently extract and convert natural resources into goods is one major governing factor for growth.* If you can both extract energy faster and use it more efficiently, as occurred in the U.S. from the 1930s to early 1970s (Fig. 6.1), you can literally and physically power more economic activity.

Think about it like this. Imagine you have the most sophisticated drilling rig in history, but if you drill in a spot with no oil and gas, your drilling rig doesn't extract anything. That is a total loss of money and waste of energy. This is why oil and gas companies spend so much time and money understanding Earth's geologic history. It's important to know *where* to drill. We can certainly describe drilling rigs and seismic imaging methods today as higher quality capital than those 40 years ago. This capital is also designed by people who must have time to research and develop knowledge for new designs.

A physical drilling rig by itself does not promote growth. Growth is enabled by providing the fuel to the economy when the drilling rig performs the useful work of poking a hole into Earth to release oil and gas from where it resides. The same concept holds for wind turbines and solar panels. The first ones we develop are not that great, and we generally first place them in windy and sunny locations because we can convert more sunlight and wind into more useful work, not less. In short, you need the human-derived technology *and* the naturally occurring energy resource.

Newer economic growth models consider that investment in research and development increases our ability to design better machines that extract harder-to-get resources. Paul Romer recently won the Nobel Prize for Economics for this idea of "integrating technological innovations into long-run macroeconomic analysis" via the endogenous growth concept mentioned earlier.[46] Usually this technological innovation is attributed to increases in human knowledge, something difficult to interpret outside of the context of any reason why we need or want increased knowledge. Again, the missing component is energy and natural resources

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[46] Paul M. Romer Nobel Prize Lecture. https://www.nobelprize.org/prizes/economic-sciences/2018/romer/lecture/.

themselves. As pointed out in the last chapter, ecosystems, animals, and economies are characterized by a similar mathematical scaling law linking their energy consumption and size. If we attribute this same pattern in the economy as due to "technology," then do we think ants are also developing new technology as they grow their colony?

Learning economics without incorporating the principle that energy is a required input for all activities is akin to depriving animals of critical stimuli during brain development. Recall from the last chapter that animal brains can lose the capability to sense certain stimuli if never exposed to the stimuli. Thus, to make useful growth models we must stimulate our brains with both economic and physical concepts.

> Economists might find it hard to learn how to integrate energy into their thinking just as energy scientists and engineers might find it hard to learn to integrate economics into their analyses. But this cross-learning does happen, and it needs to happen more often.

As pointed out by Wexler's quote at the beginning of this subsection, *our culture is partly defined by our economics, and the battle for control of culture is continuous*. If this is true, then to change our culture more people need to learn and practice improved economic principles. To close the loop on brain stimulation and learning economics, a review of existing studies concluded that students taught neoclassical economics become less moral than their peers. Apparently, the focus on self-interest and consumer goods "…renders those influenced by its teachings less moral and more antisocial."[11].

While the previously quoted macroeconomics texts are a couple of decades old, mainstream economic discussion of technology still focuses on TFP and the Solow model that lacks explicit resource input. Robert Gordon's 2016 tome *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War* is a popular recent book with significant focus on TFP trends [19]. Gordon uses his own extensive research regarding what he feels is large undercounting of GDP, and, importantly, actual personal welfare, when significant new products first come into the market. Ford's Model T is an example of a new product he describes as undercounted within GDP. Also, receiving the same income while moving from a 60 h to a 40 h work week is a large gain in welfare—same pay, fewer working hours.

These welfare and accounting concerns are very relevant, but here we will focus on Gordon's discussion of trends in TFP. Gordon refers to total factor productivity as "the best available measure of innovation and technical change."[47] However, as I've hammered home, there is a problem with the typical interpretations of TFP by Gordon and neoclassical economists. They cannot distinguish the quality of an energy extraction technology from the quality of the resource it extracts.

Consider drilling for oil. The following two scenarios would not be distinguishable. Assume the use of a vertical drilling rig, with no hydraulic fracturing

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[47] Gordon [19, p. 546].

capability, as the same "technology." Scenario 1 is drilling in the prolific east Texas oil fields in the 1930s (e.g., Spindletop), and Scenario 2 is drilling into the tight sand and shale formations now pursued in the Bakken formation of North Dakota and the Permian Basin of West Texas. By no means would you extract the same amount of oil from drilling one well into each rock formation in its original condition. In Scenario 1, you would produce enough oil to become a millionaire and trigger the age of oil, and in Scenario 2 you would go broke. The difference between the scenarios is the resource size and quality because the human-made technology is exactly the same in both. Of course, the combined new technologies of horizontal drilling and hydraulic fracturing are partially responsible for companies' ability to feasibly extract oil from tight sands. I say partially, because the coupling of consumers and producers within networks, as discussed in Chap. 5, induced changes in technologies, namely more fuel efficient cars, that make the more costly oil extraction affordable to consumers.

To show TFP is agnostic as to the energy narratives, the same problem holds in assessing renewable energy technologies. Technology capability would seem the same whether you installed a 10% efficient solar panel in sunny Phoenix, Arizona versus a 20% efficient panel placed in Seattle that has half the annual sunshine. The reason is that the same amount of (annual) electricity would be generated in both situations even though Seattle has a more capable technology in a poorer solar resource. Clearly a 20% efficient solar panel must have a different human-based design than a 10% efficient solar panel. The more efficient technology is needed with respect to, not in spite of, the quality of the solar resource. We should interpret this in no other way.

In short, TFP cannot distinguish between the quality of an energy resource itself and the technology that extracts the resource. This distinction is obvious: technological widgets are invented by humans, but natural resources aren't. We shouldn't include natural resources in any definition of human-derived technology, but that is what TFP inherently does.

Figure 6.2 shows Gordon's calculation of TFP as decadal averages, the same method as displayed in his book.[48] He describes 1920–1970 as the period in U.S. history with the highest growth in TFP. In particular he calls the 1920s through 1950 the "Great Leap." The decades after the 1970s show a marked decline in TFP. Together, these two time periods represent the rise and fall, respectively, governing the title of his book. Figure 6.2 also shows a second estimate of TFP from the U.S. Federal Reserve Bank of San Francisco, and later we'll compare those data to changes in useful work efficiency of Fig. 6.1.

Gordon asks a good basic question: "What allowed the economy of the 1950 and 1960s so unambiguously to exceed what would have been expected on the

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[48] Gordon [19, Figure 16-5].

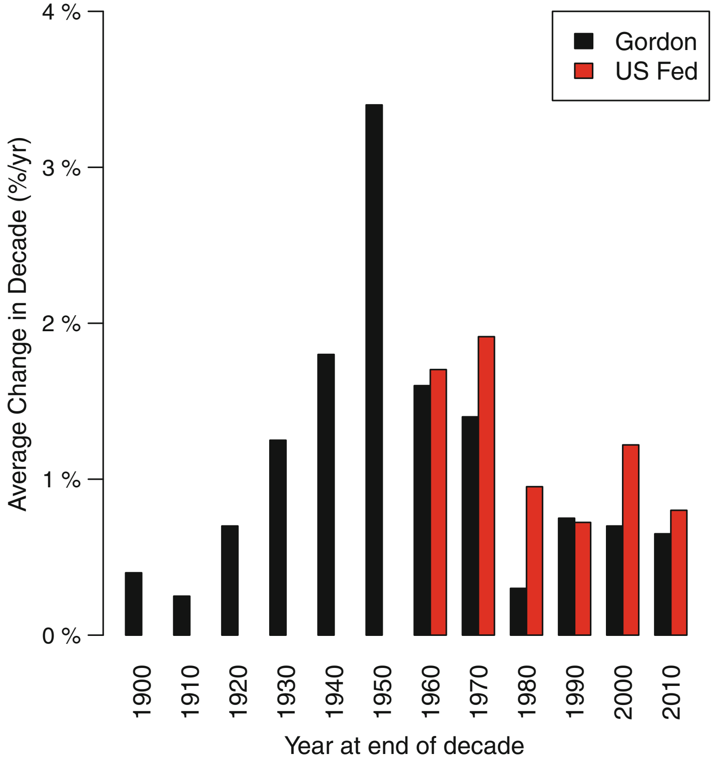

Fig. 6.2 Average change in Total Factor Productivity (TFP) by decade as reported by Robert Gordon (black, left columns, 1900–2010s) and the U.S. Federal Reserve (red, right columns, 1960–2010s) [13]

basis of trends estimated from the six decades before 1928?”[49] We will find that his explanations are consistent with the physically grounded concept that more capital, combined with the energy input to operate it, largely describe increases in “productivity” of the U.S. economy. Strangely, he seems not to see the corollary—if you can’t afford or lack either new capital *or* the energy to operate capital, this can explain poor gains in productivity.

Gordon defines the Great Leap by a significant jump in wages ($/hour) and GDP per hour worked. The post-Depression New Deal legislation, such the Fair Labor Standards Act, empowered unions and significantly increased the number of workers covered by 8 h work days with overtime pay. The two decades after the Great Depression were unique in timing for making use of and refining relatively new technologies:

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[49] Gordon [19, p. 536].

> "…there was a leap in TFP between 1929 and 1950 as real GDP more than doubled even as labor and especially capital input grew far less rapidly. Our search for an explanation centers on the timing and magnitude of the Great Depression and World War II, both of which caused the inventions of the second industrial revolution, particularly electric motors and assembly-line methods, to have their full effect on productivity years earlier than might have otherwise occurred."[50]

Gordon also argues that the extraordinary investment in wartime manufacturing facilities, financed by the government and essentially free to the owners, provided such an increase in the number of factories that their boost in output brought the U.S. out of the secular stagnation of the post-Depression years: "The number of machine tools in the U.S. *doubled* from 1940 to 1945, and almost all of these new machine tools were paid for by the government rather than by private firms."[51] When you are buying a lot more tools, particularly paid for by someone else, you can accelerate the purchases of new technologies like electric motors, and redesign factory layouts to take advantage. Thus, the few decades after World War II saw fewer total working hours per person and increasingly higher wages than during the 1920s.[52] Gordon argues that these higher wages incentivized investment to substitute capital (machines) for the higher-cost labor.

> It is likely that electric power and the assembly line explain not just the TFP growth upsurge of the 1920s, but also that of the 1930 and 1940s. There are two types of evidence that this equipment capital was becoming more powerfuel and more electrified. First is the horsepower of prime movers, … and the second is kilowatt hours of electricity production.[53]

Gordon recognizes that these more powerful factories experienced a "…vast increase in the amount of electricity consumed per unit capital." This translates to an increase in useful work to produce more products, but without a need to increase the hours per worker. Just as machines substituted for physical labor in the farm, they did so in the factory. He notes that the U.S. reached the peak GDP per hour worked in 1972 after an unprecedented 40-year increase.[54] In Fig. 5.4 of Chap. 5 we've already seen that residential energy consumption per household also increased rapidly from World War II until peaking in 1972. Thus, more GDP per hour worked and more of GDP going to workers through 1970 meant consumers could buy larger houses that contained more appliances that consumed more energy. The year 1973 is also the peak in total U.S. energy consumption per person. (In the next chapter, we'll summarize many U.S. data trends in one location to more easily see linkages between energy consumption and economic indicators.) Just as 1973 seemed as convenient of a year as any for Blanchard to choose for the end of a time of anomalous growth, Gordon does not mention 1972 as having any relevance related to the 1970 peak in U.S. conventional oil extraction or the subsequent OPEC

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[50] Gordon [19, p. 528].

[51] Gordon [19, p. 553].

[52] Gordon [19, p. 537].

[53] Gordon [19, p. 557].

[54] Gordon [19, Table 16-1 and Figure 16-3].

oil price increase in 1974. This in spite of the fact that Gordon recognizes two energy-related trends that ended in the early 1970s.

First, "…between 1929 and 1950, motor vehicle horsepower tripled and total electricity production rose 3.3 times."[55] Second, the "…epochal moment in the history of the American petroleum industry occurred with the discovery, in October 1930, of the east Texas oil field, which has been called "the largest and most prolific oil reservoir in the contiguous United States."[56] That epoch ended in 1970.

The explanation seems to be just outside of his grasp when Gordon recognizes the value of increased use of electricity for manufacturing and oil for transportation fuels during the Great Leap. He doesn't quite buy the direct energy-economic relationship, because in describing the lack of growth in TFP after 2000 he states "The most recent decade, 2004–14, has been characterized by the slowest growth in productivity of any decade in American history … "[57] This decade also corresponds to some of the highest average real oil and natural gas prices in U.S. history (recall Fig. 3.1) and follows the year when U.S. energy and food costs as a share of GDP generally stopped declining (Fig. 2.9). Aside from the decades of the 1930s during the Great Depression as well as 1973–1983, the period of 2004–2018 is the only span in U.S. history with a constant level of primary energy consumption (recall Fig. 2.7).

The key missing factor by Gordon, and neoclassical economists in general, is the feedback from the cost of energy. This is largely because their "…search for explanations begins with elementary economics."[58] By "elementary economics," he means neoclassical theory:

> To explain the upsurge in labor productivity [during the Great Leap], the best place to start is with basic economic theory. In a competitive market, the marginal product of labor equals the real wage, and economists have shown that labor's marginal product under specified conditions is the share of labor in total income times output per hour. If the income share of labor remains constant, then the growth rate of the real wage should be equal to that of labor's average product, the same thing as labor productivity.[59]—Robert Gordon (2016)

His "basic economic theory" is *too* basic, and the "specified conditions" are the neoclassical assumptions. Here is a rephrase of the quote above to indicate what he really means, with italics indicating where I have rephrased his words:

> To explain the upsurge in labor productivity, the *usual* place to start is with *neoclassical* economic theory. *If* a *fully* competitive market *exists, which it practically never does*, the marginal product of labor equals the real wage, and economists have *assumed* that labor's marginal product under *the assumptions of neoclassical theory, such as equilibrium*, is the share of labor in total income times output per hour. If the income share of labor remains constant*, but unfortunately the data indicate that it has not since the 1970s*, then the growth

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[55] Gordon [19, p. 559].

[56] Gordon [19, p. 560].

[57] Gordon [19, p. 529].

[58] Gordon [19, p. 537].

[59] Gordon [19, p. 541].

> rate of the real wage should be equal to that of labor's average product, the same thing as labor productivity.—rephrase of passage in Robert Gordon [19, p. 541]

Remaining stuck with basic economic theory, Gordon's major explanation for the growth of his Great Leap is that the Great Depression (and World War II) directly contributed to the high growth rates because it spurred the legislation of the New Deal:

> …with its NIRA and Wagner Act that promoted unionization and that directly and indirectly contributed to a sharp price in real wages and a shrinkage in average weekly hours. In turn, both higher real wages and shorter hours helped to boost productivity growth rapidly in the late 1930s, before the United States entered World War II. Substitution from labor to capital as a result of the jump in the real wage is evident in the data on private equipment investment, which soared in 1937–41 substantially above the equipment investment:capital ratio of the late 1920s.—Robert Gordon (2016)[60]

So Gordon claims that total factor productivity, and thus economic growth, increased during the Great Depression because the mandate for higher wages incentivized businesses to use machines instead of people. While I agree businesses faced this motivation, it misses a larger point.

> Without both the machines *and the energy to operate them* there could not have been the increase in economic growth and output per worker witnessed from the 1930s to the 1970s.

It was not only the proliferation of power plants and motors, but also the availability of coal to burn and water to flow through dams that represent the absolute physical necessities for power generation.

Further, studies of the mathematics behind the "basic economic theory" of the Solow growth model show that Gordon is mathematically correct when he states that "higher real wages" helped boost productivity. Jesus Felipe and John McCombie derived that what neoclassical economists call TFP is in fact based only on a mathematical identity used to define GDP. TFP is simply an average of the change in wages and the change in the rate of profit on capital [12].[61] So yes, by mathematical construct, if real wages increase, then TFP increases! Changing wages have absolutely nothing to do with either human ingenuity or anything physically tangible that we might call "technological change." All companies could raise the wages of all workers tomorrow without changing any machines or consuming any more energy, and yet these changes would affect the calculation of TFP, what Gordon calls "…the best available measure of innovation and technological change."[62]

When it comes to understanding the role of energy for the economy, we don't have to throw away neoclassical economic theory if it works, but it is not the

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[60] Gordon [19, p. 563].

[61] Using the standard "cost shares" of 0.7 for wages and 0.3 for labor, the change in TFP is thus 0.7 times the rate of change of wages plus 0.3 times the rate of change of the profit rate.

[62] Gordon [19, p. 546].

"best place to start" because it doesn't sufficiently explain long-term growth and TFP. As I now explain, we have a technological characteristic, that we can directly measure, that relieves us from using the neoclassical growth model and TFP as an explanation for "technological change," "human ingenuity," or practically any concept of "progress" someone wants to attribute to it.

What makes more sense is to think of the economy, like animals and ecosystems, as a physical metabolic system that consumes and dissipates energy in order to grow and maintain itself. To understand these systems, the places to start are the conservation laws of physics and thermodynamics. These conservation laws have assumptions behind them, and they have been verified time and time again by controlled experiments.

Ayres' research considered applying the straightforward concept of useful work to modeling GDP and this eliminated much of the need for TFP:

> The efficiency of converting energy into useful work largely describes what TFP really is.

Figure 6.3 shows this is the case. *The rate of change of U.S. useful work efficiency (from Fig. 6.1) follows in lockstep with estimates of U.S. TFP. Further, useful work follows GDP.*

The implication is that we can more accurately model economic growth by projecting useful work, something we can measure and quantify, instead of assuming TFP, which we can't.

TFP by its definition within the neoclassical Solow growth model ignores many factors. This is the case with any model. The main problem with the neoclassical growth model is it ignores the obvious: energy and other natural resources must be consumed to do anything. It doesn't describe this consumption in a way that affects economic growth, and this lack of description makes it less useful than what we need. Most economists' explanations for TFP only adjust the value of quality of capital and labor without noting the real physical constraints of economic production related to energy consumption and time delays to make more capital. These constraints are normally considered in modeling the dynamics of individual businesses, just not as much for the overall macroeconomy.

Ask yourself this question: Why do we need to get smarter to design machines that have more functionality such as higher power, higher efficiency, more information processing? Of course, there are many answers, but one important answer is *to acquire more natural resources that in turn become more capital, become consumed to operate that capital, and become food for people.* These are the fundamental processes that occur in the economy. The more capital that operates, the larger the economy. The more people alive, the higher the drive to extract more resources to support their livelihoods via the operation of capital. More capital can produce more useful work if the energy system delivers more fuel to the capital. Warr and Ayres state this more explicitly: "Exergy efficiency changes with (a) improvements in the efficiency of existing technologies and (b) the innovation and adoption of new technologies which either improve the performance of existing process, or (c) cause a shift in the structure of energy service (the type of useful work) demanded." [62]

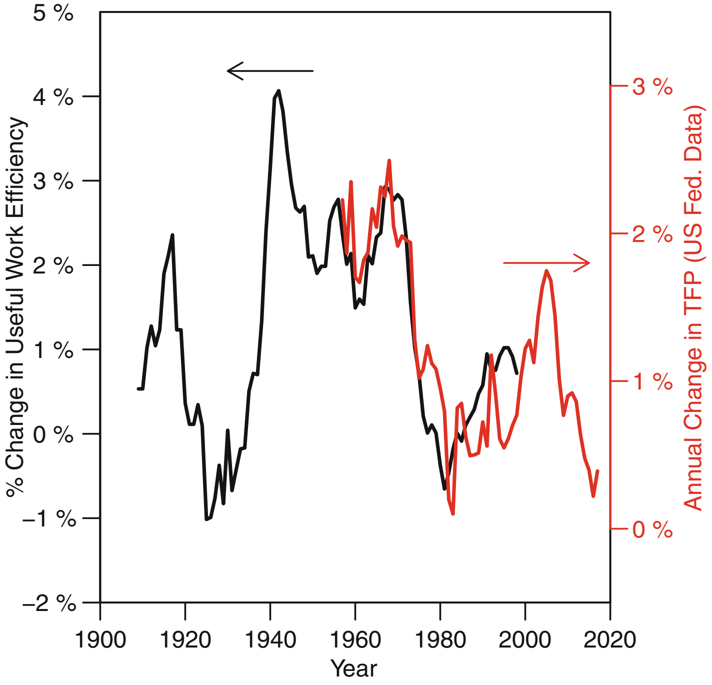

Fig. 6.3 The 10-year running average annual change in U.S. useful work efficiency compared to the 10-year running average annual change in total factor productivity (TFP) as reported by the U.S. Federal Reserve [13]. Useful work efficiency data from [62]

Figure 6.4 shows two metrics relating U.S. energy to GDP. Modelers commonly relate total primary energy to GDP by dividing the former by the latter. This *energy intensity* is the red line that declines from approximately 50 MJ/$ in 1920 to 15 MJ/$ in 2000.[63] If we instead compare Ayres' useful work to GDP to calculate *useful work intensity*, we get an approximately constant value across 100 years, ranging from 1.5 to 2.5 MJ/$.

Figure 6.5 shows these same data in a different way. It plots GDP and useful work together over time. The U.S. data are in subfigure (a), and the same calculations are shown for three other countries (U.K., Austria, and Japan). The high correlation between GDP and useful work is clear to see.

For the U.S., we see that useful work and GDP grew at almost the same near-exponential rate, both increasing nearly 15 times over the twentieth Century. What this means is that if you know how much useful work is performed in a year, then you just need to multiply that by some constant number to estimate GDP

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[63] The data used from Warr et al. [62] are for primary exergy, not energy, but they are quite similar. Here and in the figure I use the term energy for simplicity of discussion.

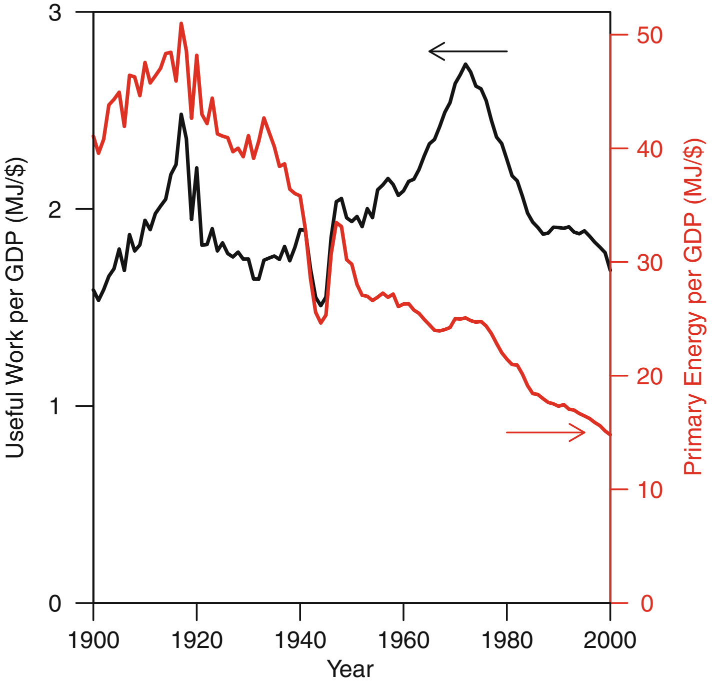


Fig. 6.4 (left axis) U.S. useful work intensity (= primary energy times conversion efficiencies to useful work divided by GDP). (right axis) U.S. primary energy intensity (= primary energy divided by GDP). Real GDP, energy, and useful work data from [62]

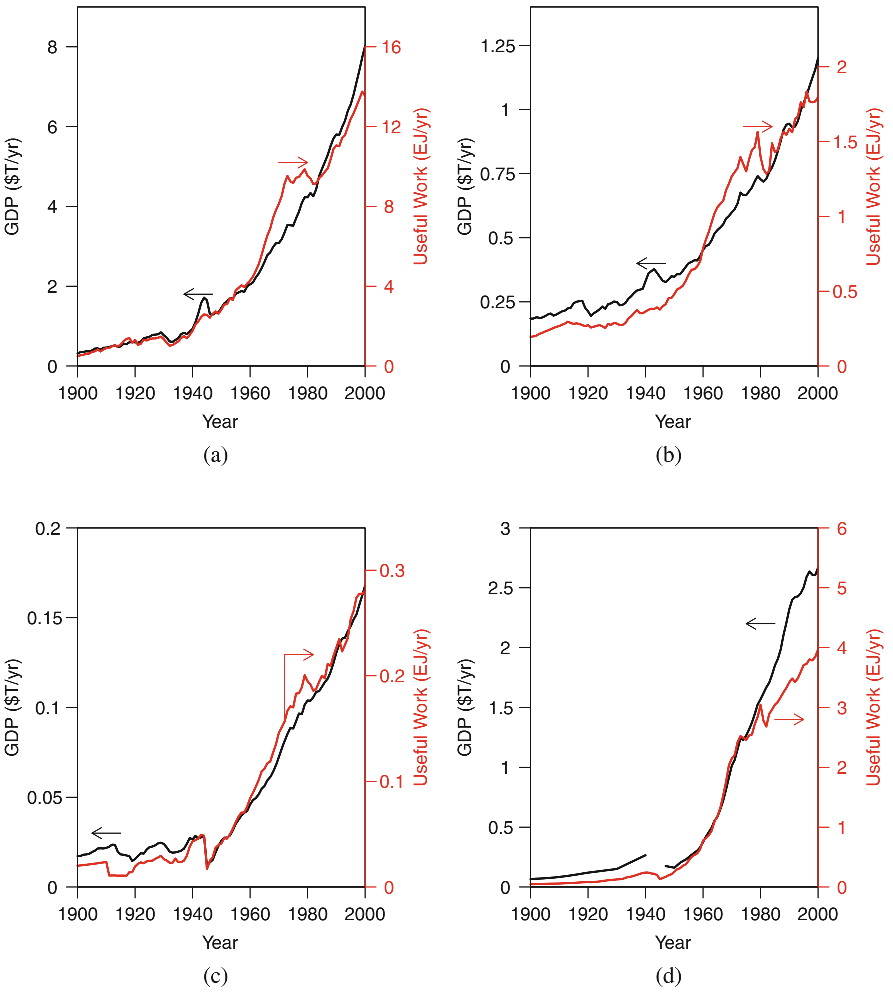
more accurately than the Solow neoclassical growth model. For the U.S., we can approximate trillions of dollars of U.S. GDP quite closely simply by dividing each one billion joules of useful work by 1.9. Of course, we have to diligently calculate useful work from known data, but that is a more concrete task than trying to figure out exactly all changes in the world that could possibly describe total factor productivity.

The conclusion is clear.

> If we want to model GDP, we should include the concept of energy and its efficiency of use by machines, or the useful work of the economy.

This answers a question that Robert Solow himself asked in 2007, 50 years after he derived his original growth model:

> There is also a …long-standing worry of mine. We estimate time series of TFP in the conventional way, more or less completely detached from the narrative of identifiable technological changes that a historian would produce for the same stretch of time. There are reasons for this disjunction. TFP is estimated for aggregates, for a whole industry at a minimum, whereas the historical narrative is usually about single firms or even single individuals. Both temporal aggregation and cross-sectional aggregation will mask



(a)

(b)

(c)

(d)

Fig. 6.5 GDP and useful work (= primary energy times conversion efficiencies to useful work) for (**a**) the U.S., (**b**) the U.K., (**c**) Austria, and (**d**) Japan. Real GDP, energy, and useful work data from [62]

> individual events. . . . it would be interesting to see if any connection can be made, perhaps in a specific industry, between the time series of TFP and an informed narrative of significant innovations and their diffusion. (One can see in principle how TFP should be related to new-product innovations, but it is not clear what would happen in practice.) [59]—Robert Solow (2007)

Well, an ". . . informed narrative of significant innovations . . . " that informs what does ". . . happen in practice . . . " is the story of thermodynamic energy conversion efficiency, and efficiency very much follows that of TFP. Steve Keen, Robert Ayres, and Russell Standish go even farther. They say that we should actually stop using our current calculation of GDP and replace it with the calculation of useful work [32]!

The statement brings up an important question: just what is GDP measuring? If GDP in some approximate way measures what we value, are we inherently valuing useful work without thinking about it? We'll save more philosophical discussion of the purpose of the economy for Chap. 8. But before we get there, it's important to think about perhaps the most important energy policy implications of economic modeling: the cost and feasibility of transitioning to a low-carbon energy system.

Neoclassical Growth: Problems for Policy

It is hard to overstate the policy implications of relying too heavily on the neoclassical model, and in particular the Solow model with exogenous technology as total factor productivity (TFP). To project future economic growth using the Solow growth model you must assume future growth of TFP. By assuming TFP, the modeler effectively assumes about one-half of economic growth out of faith and ignorance because TFP is by definition independent of any policies or parameters within the model. You could assume no growth in TFP, but if you did you wouldn't be able to mimic historical GDP trends or have any reasonable say about GDP in the near-term future.

Consider the ramifications of using TFP and neoclassical growth theory to discuss the energy narratives. Due to concerns regarding climate change, we want to understand the economic impacts from transitioning to 100% renewable energy or a low-carbon energy system with near-zero greenhouse gas emissions. There are many reasonable questions. Does a transition from fossil to renewable energy promote or inhibit economic growth? How does the speed of a low-carbon transition affect the economy?

Researchers use integrated assessment models (IAMs) to help discuss these questions. These IAMs link models of the Earth's climate to models of the economy. Because we want to specify the shift to low-carbon energy, the economic part of IAMs must represent different types of energy resources and technologies from biomass power plants to oil drilling rigs. And now we see the crux of the problem: *IAMs based on neoclassical growth theory assume that economic growth is not affected by the quantity, conversion efficiency, or cost of energy inputs.* How can models that assume energy has no role in economic growth explain the economic impact of a new energy system? They don't. And they can't.

Think of it this way:

1. We want to know how the economy responds if we convert to a low-carbon energy system composed of renewable energy and storage technologies, nuclear power plants, systems that capture carbon dioxide and inject it underground, and maybe even technologies that take carbon dioxide directly from the air.

2. Integrated assessment models (IAMs) link climate models to economic models that use TFP and neoclassical growth theory to project future economic output.
3. Neoclassical growth models using TFP assume growth is not a function of energy inputs, conversion efficiencies, or costs. This is the same as assuming energy will always be available at low cost and at any rate needed.
4. Thus, economic output from IAMs is unaffected by changes specific to a low-carbon energy system.

The result from most IAM models is that no matter what, the economy always grows! Stay high carbon? Economy grows a lot. Going to zero-carbon emissions? Economy still grows a lot. The reason is that instead of assuming how the rate of investment and cost to convert to a low-carbon energy system affect economic growth, most IAMs generally assume economic growth first, via TFP, and decide later how many ways you can reconfigure the energy system.

Importantly, almost all of today's economic models used to understand a renewable or low-carbon energy transition assume a variation of neoclassical growth. Included in this list is the famous DICE model (Dynamic Integrated model of Climate and the Economy) of William Nordhaus, a model used to explore U.S. climate policy and the price of carbon we might charge ourselves to incentivize reductions in greenhouse gas emissions [50]. Because the IAMs don't actually answer the question that we really want to ask (What are the economic impacts of an energy transition?), this is misleading to climate advocates. Consider this quote from a blog post "It's Not Too Late To Stop Climate Change, And It'll Be Super-Cheap":

> To be crystal clear, my position—what the literature and field experience make crystal clear—is that solving climate (stabilizing at 2 °C) is cheap, by any plausible definition of the word. Indeed, it is "super-cheap." … "The always overly-conservative Intergovernmental Panel on Climate Change reviewed the entire literature on the subject and concluded the annual growth loss to preserve a livable climate is 0.06%—and that's "relative to annualized consumption growth in the baseline that is between 1.6 and 3% per year." So we're talking annual growth of, say 2.24% rather than 2.30% to save billions and billions of people from needless suffering for decades if not centuries.[64]—Joe Romm (2014)

Romm correctly cites the Intergovernmental Panel on Climate Change's (IPCC) summary of the IAM literature. He's also correct to be enthused that climate mitigation might reduce suffering for billions of people. However, he's incorrect in stating that the literature "concluded the annual growth loss to preserve a livable climate is 0.06%." The models didn't *conclude* this; they *assumed* it [9, 35].[65]

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[64] Joe Romm, ThinkProgress, January 29, 2015, It's Not Too Late To Stop Climate Change, And It'll Be Super-Cheap, https://archive.thinkprogress.org/its-not-too-late-to-stop-climate-change-and-it-ll-be-super-cheap-8865694dbbd2/.

[65] Also see King (2015) that discusses the model outputs used by the Fifth Assessment report of the IPCC. The report summarizes results indicating the economy would grow 250–800% from 2010 to 2100 even going to an economy with zero or negative greenhouse gas emissions by 2011. The report readily states that "negative feedbacks" from energy costs are not considered (see Figure A.II.1 of [35]).

Again, this is because the models assume energy quantities and costs play, at most, a very minor role in growing or constraining the economy. Also, his quote includes a key tell that the use of TFP or some other quantity simply are assumed to increase into the future: “annualized consumption growth in the baseline that is between 1.6 and 3% per year.” About half of that “baseline” is just assumed to occur. For an example model, consider the Global Change Assessment Model (GCAM), one of the major IAMs. GCAM projects future GDP by assuming the growth of both population and GDP per person. However, *nothing* in the GCAM model provides a way for the modeled energy system to affect the assumed GDP change and population: “Population and economic activity are used in GCAM through a one-way transfer of information to other GCAM components. For example, neither the price nor quantity of energy nor the quantity of energy services provided to the economy affect the calculation of the principle model output of the GCAM macroeconomic system, GDP.”[66]

Economic modelers can assume whatever GDP and population growth they want, but for baseline projections they typically stay within values calculated from recent history. However, as any investor reads on any mutual fund or stock prospectus, “past performance is no guarantee of future results.”

Think about the quoted GCAM assumption: “*... neither the price nor quantity of energy ... affect the calculation of ... GDP.*”! Assume something absurd such as all energy consumption stops tomorrow. In the model, GDP is the same. Do you think that “result” is useful? When we use models to pontificate future low-carbon energy scenarios that stray from historical data (such as within the energy versus GDP plot of Fig. 5.2) but provide no feedback between energy and GDP, then there is a good chance our model results will have no real meaning.

Do climate advocates know of this energy and “technology assumption” problem within macroeconomic models in IAMs? Most people do not. If they do know, would they even care? Probably not, because the models “tell” us that growth occurs in a zero-carbon world or a high-carbon world. This techno-optimistic, or should we say techno-ignorant, growth narrative helps promote climate change mitigation and adaptation just as well as it promotes the avoidance of mitigation and adaptation.

I’m not saying that I know for certain whether the economy would go into a depression if we converted to a zero-carbon world in 30 years. I’m also not saying a low-carbon economy takes us to nirvana. What I *am* saying is that neoclassical economic growth models can’t fundamentally tell us anything about the issue.

Do you believe that a zero-carbon world, one that requires actively extracting carbon dioxide from the atmosphere, has only zero point zero six percent (0.06%) less annual growth than a full-carbon-ahead world reaching 4+°C or more temperature rise by 2100? That does not pass the smell test. The models literally cannot tell the difference because their underlying theory and assumptions prevent them from doing so. Again, I make this statement only by evaluating economic model

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[66] GCAM model documentation, GCAM v5.1 Documentation: The GCAM Macro-Economic System, accessed March 21, 2019 at http://jgcri.github.io/gcam-doc/macro-econ.html.

outputs. I'm not discussing any effects from the physical changes related to higher greenhouse gas concentrations in the atmosphere. Also, as we'll discuss in the final chapter, growth isn't everything, and a focus on human level outcomes provides reasons to pursue policies for low-carbon energy and increased income equality, for examples, even if GDP declines.

Many researchers understand the flaws of neoclassical models. For example, Sgouris Sgouridis criticizes the structure of the energy-economic modeling within IAMs from another angle: the substitutability of one energy technology for another [27]. Recall the Cobb–Douglas production function assumes infinite substitution, thus by definition at the extreme end of economic narrative for techno-optimism and infinite substitution. Many IAMs use a more general form of this function known as the Constant Elasticity of Substitution (CES) production function. The CES function allows modelers to put limits on how much one input factor can substitute for another. Many of the IAMs also have "nested" structures that allow a subset of substitutable technologies to produce an output that is again one of many inputs to produce a second output, and so on for several levels of nesting.

For example, there are many ways to generate electricity as "output 1" using wind turbines, solar panels, and natural gas plants. Electricity in turn can be one input, along with capital and labor, for stationary power and heat as "output 2." Then stationary power and heat can be one input of many to produce the ultimate "output 3" of GDP. However, this substitution game is still played mostly in the context of monetary costs of technologies rather than on their physical capability. As Sgouridis and his co-authors note: "One would assume that a review of empirical findings should be a critical first step when modeling transitions. Yet Rosen and Guenther [54] found no literature comparing investment decisions for energy-consuming equipment implicit in IAMs with real-world trends in the past, ..." [27].

The study they refer to actually states current IAMs are of no use to estimate costs of transitioning to low-carbon energy: "Because of these serious technical problems, policymakers should not base climate change mitigation policy on the estimated net economic impacts computed by integrated assessment models." [54] Thus, while the CES concept seems like a step in the right direction, in practice it has not delivered. The problem is still that the economic theory assumes at some level that "...non-physical inputs of knowledge and capital can somehow substitute for energy thus reducing the economic energy intensity." [27].

We should use models that explicitly track the flows of energy and other natural resources so that we can include both realistic substitutions and physical constraints. These approaches have produced tremendous insight. The problem is that they've been attacked by prominent mainstream economists because, well, the models are different than what they know and use.

Attack on *The Limits to Growth*

Given the documented inaccuracies of predominant economic growth frameworks, what other modeling frameworks exist, and are they any better? These are reasonable questions. Other modeling researchers, myself included, have developed alternatives to study energy-economic interactions. But there are not enough of us.[67]

One of the most discussed and well-known models of world dynamics is World3, the model used in three versions (1972, 1992, 2004) of *The Limits to Growth* book (first mentioned in Chaps. 1 and 2) [43–45]. This model was based upon the work of Jay Forrester, the father of what is known as *system dynamics* modeling. In the 1960s while working at the Massachusetts Institute of Technology, Forrester developed the method to simulate the interactions among various elements in a way that could explain complex trends and data, such as some of those discussed in Chaps. 4 and 5. Forrester created the basic structure for the model that became World3 [15], the first relatively complex computer model to simulate the dynamics of "...five major trends of global concern—accelerating industrialization, rapid population growth, widespread malnutrition, depletion of nonrenewable resources, and a deteriorating environment."[68] As shown in the previous chapters, there were several global energy and population growth trends that seemed as though they could not continue. Growth of energy consumption and population was increasingly exponential until the early 1970s. In the 1960s in many U.S. cities, pollution was readily apparent as a problem (e.g., smog in Los Angeles, the Cuyahoga River catching fire in 1969 due to industrial pollution in Cleveland). People wanted to know why these trends were occurring and what, if anything, could be done about them.

World3 was meant to improve our understanding of global, not local, trends using graphs. As the modelers stated: "...for world population, capital, and other variables on a time scale that begins in the year 1900 and continues until 2100. These graphs are not exact predictions of the values of the variables at any particular year in the future. They are indications of the system's behavioral tendencies only."[69] Note here that the modeled system is the *global* economy and population, and the purpose is to explore "behavioral tendencies."

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[67] For examples the papers of Roert Ayres [1, 2, 62, 63] and recently combined with Steve Keen of Kingston University in London [32], a recent IAM by Bovari et al. that does not use neoclassical theory [7], research at the University of Leeds (e.g., the "MARCO-UK" model [55]), the Center for the Understanding of Sustainable Prosperity at the University of Sussex [24, 25], conceptual modeling of Tim Garret of University of Utah [16, 17], modeling of the economy as a large distribution network consuming energy to operate and grow by Andrew Jarvis [26], the ENERGY2020 model (of Systematic Solutions) which is a child of the FOSSIL2 system dynamics model of the U.S. economy that was derived from the same concepts as the World3 model, and my recent "HARMONEY" model [34].

[68] Meadows et al. [44, p. 21].

[69] Meadows et al. [44, p. 92–93].

In order to create this system model, piece by piece, the World3 team utilized "…the most basic relationships among people, food, investment, depreciation, resources, output relationships that are the same the world over, the same in any part of human society or in society as a whole. …there are advantages to considering such questions with as broad a space-time horizon as possible. Questions of detail, of individual nations, and of short-term pressures can be asked much more sensibly when the overall limits and behavior modes are understood."[70]

This last sentence is very informative and insightful. How are we supposed to understand the trends of each country, town, citizen, and energy resource if we have a poor conceptualization of the broader limits and patterns of the global economy within which they reside? We need the broad perspective to understand the purpose of the world system. As mentioned in Chap. 5, *The Limits to Growth* author Donella Meadows indicated that a system is defined by what it does. In their 1972 assessment, she and her co-authors concluded that:

> The apparent goal of the present world system is to produce more people with more (food, material goods, clean air and water) for each person.[71]— Donella H. Meadows et al. (1972)

We will return to the question of the purpose of the world system, and whether we are capable of understanding it, in Chap. 8. What's important to understand now is that the study was both praised and vilified. Why? A restatement of their three main conclusions from 1972 summarizes:[72]

1. If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next 100 years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.
2. It is possible to alter these growth trends and to establish a condition of ecological and economic stability that is sustainable far into the future. The state of global equilibrium could be designed so that the basic material needs of each person on earth are satisfied and each person has an equal opportunity to realize his individual human potential.
3. If the world's people decide to strive for this second outcome rather than the first, the sooner they begin working to attain it, the greater will be their chances of success.

They stated that *if the present growth trends* through the 1960s continue then limits to growth will be reached, not next year, or next decade, but broadly sometime in the next 100 years. In Chap. 2 we see that the global energy consumption data was growing at a near constant exponential growth rate from 1900 *until* 1973, just *after The Limits to Growth* was published.

The techno-realism narrative states that exponential growth on a finite planet can't continue indefinitely. The global data verify this

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[70] Meadows et al. [44, p. 96].

[71] Meadows et al. [44, p. 86].

[72] Meadows et al. [44, p. 23–24].

> statement as the pre-1970 global exponential growth trends in fact did not continue on the finite Earth after the 1970s.

Chalk one up for the World3 model of *The Limits to Growth*. Unfortunately, many critics misinterpreted the statements within *The Limits to Growth* with regard to exponential growth, and this continues through today. Andrew McAfee's 2019 book *More from Less* states that *The Limits to Growth* is "far gloomier" than other writings he already thinks are gloomy [42].[73] We should avoid using qualitative and vague terms, such as gloomy, to discuss very specific mathematics. Aside from that, McAfee summarizes findings from *The Limits to Growth* as follows:

> The most generous estimate of future resource availability included in The Limits to Growth assumed that exponential consumption would continue, and that proven reserves were actually five times greater than commonly assumed. Under these conditions, the team's computer models showed that the planet would run out of gold within 29 years of 1972; silver within 42 years; copper and petroleum within fifty; and aluminum within fifty-five.
>
> These weren't accurate predictions.[74]—Andrew McAfee (2019)

He goes on to ask:

> How could these predictions about resource availability, which were taken seriously when they were released, have been so wrong?[75]—Andrew McAfee (2019)

My response to McAfee's question is that his question is misleading. A reading of the passage from Chapter 2 of *The Limits to Growth* on which McAfee bases his statements shows his interpretation is incorrect. I copy the original text such that you can see for yourself that in no way did *The Limits to Growth* authors claim to *predict* when, or that there even would be a time, in which any specific mineral such as gold, silver, copper, petroleum, or aluminum would "run out." For the passage below, keep in mind they describe chromium only as a specific example of more broadly considering individual fossil minerals (in Table 4 of their Chapter 2) as well as their aggregation:

> The world's known reserves of chromium are about 775 million metric tons, of which about 1.85 million metric tons are mined annually at present. Thus, at the current rate of use, the known reserves would last about 420 years. The dashed line in figure 11 illustrates the linear depletion of chromium reserves that would be expected under the assumption of constant use. The actual world consumption of chromium is increasing, however, at the rate of 2.6% annually. The curved solid lines in figure 11 show how that growth rate, if it continues, will deplete the resource stock, not in 420 years, as the linear assumption indicates, but in just 95 years. If we suppose that reserves yet undiscovered could increase present known reserves by a factor of five, as shown by the dotted line, this fivefold increase would extend the lifetime of the reserves only from 95 to 154 years.[76]
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> ...

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[73] McAfee [42, p. 119].

[74] McAfee [42, p. 119–120].

[75] McAfee [42, p. 120].

[76] Meadows et al. [44, p. 61].

> Figure 11 shows that under conditions of exponential growth in resource consumption, the static reserve index (420 years for chromium) is a rather misleading measure of resource availability. We might define a new index, an "exponential reserve index," which gives the probable lifetime of each resource, assuming that the current growth rate in consumption will continue. We have included this index in column 5 of table 4. We have also calculated an exponential index on the assumption that our present known reserves of each resource can be expanded fivefold by new discoveries. This index is shown in column 6. The effect of exponential growth is to reduce the probable period of availability of aluminum, for example, from 100 years to 31 years (55 years with a fivefold increase in reserves). Copper, with a 36-year lifetime at the present usage rate, would actually last only 21 years at the present rate of growth, and 48 years if reserves are multiplied by five. It is clear that the present exponentially growing usage rates greatly diminish the length of time that wide-scale economic growth can be based on these raw materials
>
> Of course the actual nonrenewable resource availability in the next few decades will be determined by factors much more complicated than can be expressed by either the simple static reserve index or the exponential reserve index.[77]

Pay attention to wording such as "at the current rate of use" and "under conditions of exponential growth." In this way the full sequence of interpretation of the above excerpt from *The Limits to Growth* is the following:

1. If you assume exponential growth in consumption of a mineral continues unabated, and
2. if you assume five times more reserves of that mineral than was known in 1970, then
3. the world would extract all of those reserves after a certain number of years, but these static and exponential reserve indices are too simple to explain what will actually occur.

The *The Limits to Growth* authors clearly assumed that exponential growth cannot continue on a finite planet. That is the point of the book, and the title of the chapter to which McAfee refers is "The Limits to Exponential Growth." The plots of simulated chromium usage (Figures 12 and 13 in *The Limits to Growth*) show that they know 100% of chromium, or any fossil resource, will never be extracted because price rises with depletion, and "The higher price causes consumers to use chromium more efficiently and to substitute other metals for chromium whenever possible."[78] One of the limits to exponential growth is that you can't afford to extract 100% of the mineral.

The Limits to Growth also considered the effects of rising costs of depletion of all nonrenewable minerals in aggregate. Depending on your point of view, the *The Limits to Growth* authors' 1972 prediction of a cessation to growth "within the next one hundred years" is on par with or even bolder than that of M. King Hubbert's correct prediction of the timing of a peak in conventional U.S.-48 oil production over 10 years before it happened in 1970. At the time they were quite confident in this very general conclusion, stating that "…the basic behavior modes we have

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[77] Meadows et al. [44, p. 62–63].

[78] Meadows et al. [44, p. 65].

already observed in this model appear to be so fundamental and general that we do not expect our broad conclusions to be substantially altered by further revisions."[79] In 2004, via their 30-year update to the original book, the authors stuck with their "broad conclusions" from 1972 [45]:

> For those who respect numbers, we can report that the highly aggregated scenarios of World3 still appear, after 30 years, to be surprisingly accurate. The world in the year 2000 had the same number of people (about six billion–up from 3.9 billion in 1972) that we projected in the 1972 standard run of World3. Furthermore, that scenario showed a growth in global food production (from 1.8 billion tons of grain equivalent per year in 1972 to three billion in 2000) that matches history quite well. Does this correspondence with history prove that our model was true? No, of course not. But it does indicate that World3 was not totally absurd; its assumptions and our conclusions still warrant consideration today.[80]

They state that the World3 model was *not totally absurd*, and I whole-heartedly agree. What's important to understand now is that the general concept and structure of the model has stood the test of time very well. Other reassessments show the model effectively describes global macro trends that have taken place in the 40+ years since the original study [25, 60]. You cannot find another model that predicted trends to the degree of consistency as World3. As stated in the summary by Tim Jackson, Professor of Sustainable Development at the University of Surrey, and Robin Webster: "There is unsettling evidence that society is still following the 'standard run' of the original study—in which overshoot leads to an eventual collapse of production and living standards." But, when you start talking about declining living standards and end of growth, you will find some critics, and some are (or were) prominent economists.

Ugo Bardi's book *The Limits to Growth Revisited* details the history of *The Limits to Growth* and its criticisms [4]. He discusses how William Nordhaus and other mainstream economists misinterpreted the modeling approach because the system parameters, feedbacks, and lookup tables that influenced the dynamics were unfamiliar. For example, in Nordhaus' 1992 paper he stated: "Both models [Limits to Growth 1972 and 1992] rule out ongoing technological change. In this respect, they are inconsistent with the standard interpretation of economic history during the capitalist era."

It would be natural for a neoclassically trained economist to make this statement. This is because World3 does not include a neoclassical aggregate production function that most economists recognize and use for projecting "technological change" as non-physical total factor productivity, or human ingenuity [51]. World3 did not neglect the ability to model technological change. Because it modeled technological change via a framework and factors that differ from neoclassical theory, its structure is not conducive to many economists' "standard interpretation of economic history." This is not the same as saying the model is wrong or inaccurate, just different.

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[79] Meadows et al. [44, p. 22].

[80] Preface of *Limits to Growth: The 30-Year Update* [45].

World3 also includes a dependent structure that is similar to the net energy, or energy return on investment (EROI) concept discussed in Chap. 5 in that as resources are depleted, more capital must be allocated per unit of output to extract the next bit of resource. This concept is crucial to produce realistic feedbacks. We clearly see this "more capital with depletion" in data associated with unconventional oil production and solar panels because they do require more capital per unit of oil and electricity than past methods. In order for a model to include this feedback, it must define an appropriate internal structure that requires an output from the economy, such as energy, to also be an input. The standard neoclassical approach, using an aggregate production function, ignores this type of feedback.

As already noted, another major criticism of World3 was its explicit consideration of a limited physical size of nonrenewable resources. World3 includes a parameter that effectively represents the maximum size of all nonrenewable resources (e.g., fossil energy and minerals) lumped together. The assumptions that the world was physically finite and that industrial output necessitated the use of resources led to a result that physical output and population could not continuously grow exponentially or indefinitely. Again, the data in Chaps. 2 and 4 show that exponential growth effectively ended in the 1970s, as predicted by World3.

In his 1992 criticism, Nordhaus did introduce a relevant question as to the role of theoretical models: "One of the major points that has emerged up to now is that the existence and significance of constraints to long-term economic growth, imposed either by environmental concerns or natural resource limitations, cannot be determined by the kinds of theoretical models [World3] developed in Limits I or II. Indeed, it is hard to see how even the best of economic models could do more than frame the questions for empirical studies to address." [51]

I disagree that models like World3 cannot be used to understand physical constraints on long-term growth, but I agree with Nordhaus that theoretical modeling constructs provide the bases for interpreting and collecting data. All models should be seen in the context of both interpreting data and the restrictions assumed by the theories and worldviews that guide the interpretation. Different worldviews present different interpretations of the same data. Martin Weitzman's discussant comments in Nordhaus' paper accurately juxtapose the worldviews of the "limits-to-growth" perspective with those of the "average contemporary economist":[81]

> There may be a some value in trying to understand a little better why the advocates of the limits-to-growth view see things so differently and what, if anything, might narrow the differences.
>
> I think that there are two major differences in empirical worldviews between mainstream economists and anti-growth conservationists. The average ecologist sees everywhere that carrying capacity is a genuine limit to growth. Every empirical study, formal or informal, confirms this truth. And every meaningful theoretical model has this structure built in. Whether it is algae, anchovies, or arctic foxes, a limit to growth always appears. To be sure, carrying capacity is a long-term concept. There may be temporary population upswings or even population explosions, but they always swing down or crash in the end because of

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[81] Martin L. Weitzman discussion in [51].

> finite limits represented by carrying capacity. And *Homo sapiens* is just another species-one that actually is genetically much closer to its closest sister species, chimpanzees, than most animals are to their closest sister species.
>
> Needless to say, the average contemporary economist does not readily see any long-term carrying capacity constraints for human beings. The historical record is full of past hurdles to growth that were overcome by substitution and technological progress. The numbers on contemporary growth, and the evidence before one's eyes, do not seem to be sending signals that we are running out of substitution possibilities or out of inventions that enhance productivity.

Studies like World3 and comments such as Weitzman's inspired me to derive models to bridge the gulf between worldviews. In this book I've emphasized the need to consider both the *size and structure of the economy*. This conclusion is informed by my research, that I now describe, that indicates how resource constraints can lead to slower growth an economic restructuring, just like the U.S. experienced following the 1970s.

Putting My Money and Energy Where My Mouth Is

I spend much of my time around engineers and scientists who design technologies and models of energy and electricity flowing within the economy. On the other hand, politicians, think tanks, lobbyists, policymakers, and other holders of the various energy and economic narratives tend to talk about how much money flows from one pocket or another. The renewable energy pocket or fossil fuel pocket. The rich, middle class, or low-income pocket. The unions or the business owners and bankers. The pocket of "Big X" (Big Oil, Big Pharma, Big Agriculture, etc.) or of small business. It is difficult for people to discuss the systemic issues presented in Chap. 5, but often easier to revert to political explanations for why money is distributed to "them" instead of "us," and Chap. 9 visits some of these narratives. Ideally we should say something about economic growth *and* distribution, or size *and* structure.

One aspect of World3 that makes it hard for some to translate to contemporary issues is that the modelers purposefully avoided explicit counting of certain economic quantities such as wages, debt, and employment. Given the increased concerns over issues of debt and wealth distribution, I thought it was time we bridge a gap between models like World3 that have much insight into human and resources dynamics but might lack concepts of distribution, and economic models that are based on the distribution of money within the economy, but have little to no insight on the role of natural resource use.

With that goal in mind, I created a model based on a similar concept as World3 in that it has an allocation of resources and capital between "energy" and "non-energy" parts of the economy, and it also includes economic factors that both economists and workers care about, such as wages and debt. This combination allows us to understand if and how energy and resource consumption play a role in the trends of debt ratios and wage inequality that we explored in Chap. 4.

It is easier to propagate your model if you give it a memorable name, and I called my model HARMONEY for "Human And Resources with MONEY" [34]. The HARMONEY model is a combination of two other existing models. The first is a very simple model of an agrarian society that harvests a forest-like resource to feed itself.[82] The second is a model of a simple economy with fluctuating business cycles, tracking physical capital, wages, and employment, while also considering the real-world tendency of businesses to invest more than their profits by borrowing money from a bank.[83] This borrowing is what "creates money" as debt within the model, just like commercial banks create money when they provide a loan to a business.

From the standpoint of natural resource use, HARMONEY has three key features that are consistent with real-world physical activities. First, natural resources are required to operate capital. This is the same as saying you need fuel to run your car, and a factory needs electricity to operate manufacturing machinery and computers. Second, natural resources are required to make new capital. This is the same as saying that all of the objects around you now (coffee mugs, computers, buildings, etc.) are made of natural resources. Third, natural resources are required to sustain human livelihood. This is the same as saying that, at a very basic level we need food to survive, and at a higher level more resource consumption leads to more longevity. Thus, whatever the flow of natural resources, those resources must be allocated between the three aforementioned uses.

From an economic theory standpoint, the model does not calculate GDP using an aggregate production function, such as the Cobb–Douglas or CES formulations. HARMONEY is simple in that it has only two types of activity. The first uses machines to extract resources, and the second uses machines to make more machines, or capital. Importantly, both activities require capital, labor, and natural resources (e.g., energy) to function, and any one of them can be the constraining factor. This enables the model to incorporate the net energy feedback of energy return on investment (EROI) and understand these biophysical metrics in the context of more common metrics of GDP, debt, wages, capital accumulation, and population growth.

The results from the HARMONEY model have an uncanny ability to mimic and explain very important long-term trends in the economy. Figures 6.6 and 6.7 show two comparisons of model results to U.S. data. Before describing the insights from these figures, an excerpt from my publication provides some context [34]:

> While the model trends show important similarity to those of the U.S., we caution that the model is not calibrated to the U.S. or any economy. …the comparison to U.S. data indicates that the model characterizes important underlying processes that govern long-term growth and structural change in an economy such as that of the U.S. For our model-U.S.

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[82] This is the HANDY, or Human And Nature DYnamics model of [48].

[83] This is Steve Keen's "Minsky" model that uses what is known as the Goodwin model but incorporates a new equation for debt creation [28, 31].

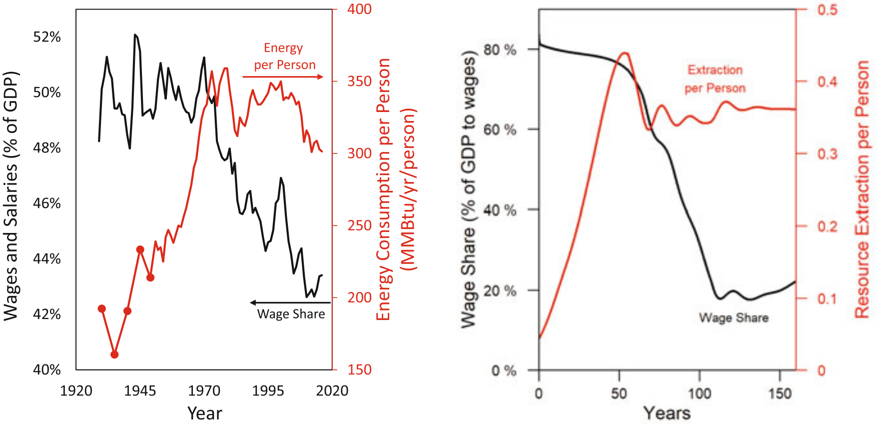

Fig. 6.6 (Left figure) Data for the U.S. wage share (left axis) and per capita energy consumption (right axis) both change their long-term trends in the 1970s. (Right figure) In the same way as the U.S. data, the wage share (left axis) from the HARMONEY model shows the same simultaneous turning point in long-term trend, from a constant value to a declining value, when per capita resource consumption reaches its peak [34]

> comparison, the general sequence of long-trends and structural change are important, not the relation of magnitudes of variables or specific model times to specific years in the U.S. data.
>
> Three reasons support comparison of the model to the U.S. First, the U.S. is relatively resource self-sufficient, and the model assumes full self-sufficiency. Second, our investment behavior matches that of the U.S. in that gross investment is significantly greater than net profits. Third, both the model and U.S. data exhibit an initial period with increasing per capita resource, or energy, consumption followed by one with approximately constant per capita consumption.
>
> This third reason is critical. The HARMONEY model assumption of an economy extracting a regenerative renewable resource inherently simulates a trend of increasing and then steady per capita resource extraction ... Thus, our model is useful for answering the question "How might the economy respond when transitioning from a period of increasing per capita resources consumption to one with steady per capita resources consumption?" It just so happens that the U.S. economy also exhibits this trend for energy consumption.

Figure 6.6 shows the wage share and per capita energy consumption of the U.S. The wage share is the percentage of GDP allocated to hourly or salaried workers, and these are the main portion of the data for total worker compensation shown in Chap. 4 (Fig. 4.12). Notice how both the wage share and per capita energy consumption have a different trend before versus after the early 1970s. Before 1973, wage share remained constant at about 50% of GDP, and energy consumption per person increased exponentially at 3%/yr. After 1973, wage share declined at about 1.5–2% per decade, and we could say energy consumption per person declined slightly or remained relatively constant.

Amazingly, the model results show practically the exact same trends as in the U.S. data. I did not anticipate this result. Also, when initially formulating the model, I

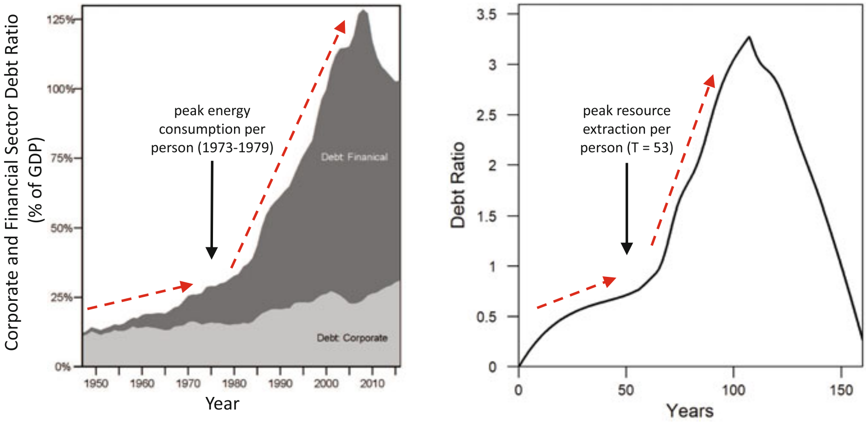

Fig. 6.7 (Left) The debt ratio of U.S. corporations and financial companies (debt/GDP) compared to (right) the equivalent debt ratio metric from the HARMONEY model [34]

had no immediate goal to mimic this type of relationship. I did want a model that had several important elements, but I didn't anticipate my first results would so clearly relate to real-world data. This wage share decline highlights one important difference for the HARMONEY model from that using the neoclassical framework: the neoclassical framework assumes a constant fraction of GDP going to wages and profits (e.g., using the Cobb–Douglas function or Solow growth model), but there is no need to make this assumption. When the real-world data show the wage share substantially declined by 7% over four decades (from 50% in 1973 to 43% in 2013), we can question any modeling approaches that simply assume a constant value. In the HARMONEY model, the wage share emerges because of how its systems-oriented structure relates the elements to one another.

The HARMONEY model also provides insight into debt accumulation. Figure 6.7 shows only two categories of the same debt data introduced in Fig. 4.6, the U.S. private company debt ratio (debt divided by GDP) for corporations and financial institutions. These two categories are equivalent to the concept of debt included in the HARMONEY model. It was the accumulation of U.S. private and household debt, and associated interest payments, that triggered the 2008 financial crisis, although the HARMONEY results did not include household debt. The crisis was not triggered by government debt.

Note how the private debt ratio increases much more rapidly after the 1970s than before, and the increase in financial sector debt drives the overall trend for the U.S. This same breakpoint occurs in the HARMONEY model and for the same reasons. In both the U.S. data and the model, when per capita resource consumption was rapid the debt ratio increased, but at a much slower rate than after per capita consumption stagnated. Recall that neoclassical theory does not account for the concept of debt, and it assumes the quantity of money has no fundamental role in long-term trends. Steve Keen's research provided a way for me to include debt into economic growth modeling [28, 31]. In his book *Debunking Economics*, Keen states the problem clearly:

> This [lack of consideration of debt], along with the unnecessary insistence on equilibrium modeling, is the key weakness in neoclassical economics: if you omit so crucial a variable as debt from your analysis of a market economy, there is precious little else you will get right.[84]—Steve Keen (2011)

Again, this is the fundamental reason why mainstream economists could not foresee or anticipate the 2008 financial crisis. They don't model debt, the cause of the crisis itself! The Queen of the United Kingdom, Elizabeth II, was wondering why (almost) no one seemed to notice the credit problem when she attended a briefing at the London School of Economics in 2008. Eight months later a group of economists sent a letter to the Queen apologizing that most economists have a failure of imagination and don't think systematically enough about how the economy operates:

> In summary, your majesty, the failure to foresee the timing, extent and severity of the crisis and to head it off, while it had many causes, was principally a failure of the collective imagination of many bright people, both in this country and internationally, to understand the risks to the system as a whole.[85]

My answer to the Queen is in this section, and I apologize for only recently studied economics, having studied only science and engineering before 2008! In addition, going back to the wage share decline, it is driven by two quantities: the accounting for depreciation for an increasing quantity of capital and the interest payments on a rising debt ratio. The pattern occurs if you assume, as observed in the U.S. data, that companies keep investing more money than their profits. Since the 1920s, U.S. corporations typically invest 1.5–2.5 times more each year than they make in profits (Fig. 4.8).[86] Thus, in this face of constant or slower increase in total energy consumption, the economy accumulates capital that either operates less or requires less energy to operate (e.g., efficient equipment, computers). Think about the patterns in Figs. 6.6 and 6.7 the following way. We can assume four major distributions of GDP (or "value added") in national economic accounting:

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[84] Keen [29, p. 321].

[85] Tim Besley and Peter Hennessy, "The Global Financial Crisis—Why Didn't Anybody Notice?", *British Academy Review*, 14, November 2009 available at https://www.thebritishacademy.ac.uk/publications/british-academy-review/global-financial-crisis-why-didnt-anybody-notice. Andrew Pierce, *UK Telegraph*, November 5, 2008, "The Queen asks why no one saw the credit crunch coming", accessed July 16, 2019 at: https://www.telegraph.co.uk/news/uknews/theroyalfamily/3386353/The-Queen-asks-why-no-one-saw-the-credit-crunch-coming.html. Associated Press, July 26, 2009, "Sorry Ma'am—we just didn't see it coming," accessed July 16, 2019 at: http://www.nbcnews.com/id/32156155/ns/business-world_business/t/sorry-maam-we-just-didnt-see-it-coming/#.XZEg_EZKhm9.

[86] See Supplemental Figure 3 in King (2019) [34] using data from the U.S. Bureau of Economic Analysis Tables 1.1.5 (GDP and gross investment) and 1.1.12 (corporate profits with inventory valuation adjustment, IVA and capital consumption adjustment, CCAdj).

government (as taxes), private profits including interest (or rent) payments to capital owners, depreciation (on capital), and wages (to workers).

In a capitalist system based on maintaining private sector profits, increases in debt ratio and the amount of capital per person means that increasing shares of GDP go to both depreciation and profits from interest payments. Because the last several decades show a constant share to government taxes,

> when there is a restriction in the growth of GDP, the prioritization of allocation to profits, taxation, and depreciation means that the workers' share is the only portion available to take the hit.

When you include debt and resources into a model, then "BINGO," out comes the insights presented in this section.

Summary: Macroeconomics

This has been a long chapter. We've covered a number of important concepts that inform mental and mathematical models we use to explain patterns in energy and economic data. One of these models is the neoclassical economic growth model. Despite its severe flaws, it reigned supreme for decades leading up to the 2008 financial crisis. The crisis exposed its major flaws, including the lack of consideration of debt and the concept of modeling the economy in equilibrium. But well before 2008, as far back as the 1970s, researchers, such as those using system dynamics methods, had devised alternative frameworks that more comprehensively and coherently described many important long-term trends of the world. Unfortunately, the critics included many proponents of the techno-optimistic narrative, including prominent mainstream economists, that simply didn't understand what they were criticizing. Policymakers listened to the mainstream, and the low energy prices in the 1980s and 1990s made people lose interest in new methods for energy-economic modeling. But there has been a resurgence in research since the turn of the twenty-first century, and this research provides improved understanding of the fundamental roles of both resources (and energy) and debt in the economy.

> Mathematical and conceptual models that consider the constraints of how energy must flow through the economy, into machines with thermodynamic energy conversion efficiencies, produce much more direct insight into how energy relates to economic output.

By including resource flows, the efficiency of converting energy into useful work, and debt into macroeconomic growth models, we can explain the broad trends of growth and structural change in modern economies over the last 50–100 years.

From a systems perspective, when growth is exponential, the system does not yet perceive any constraints or boundaries to its growth, so many more options for allocation are possible [45]. If this growth, say of energy consumption, is no longer increasing exponentially, then a different allocation of energy and money must occur, as it did in the 1970s. At some points the constraints on increasing net energy output from the resource extraction sector might cause a reduction in the flow of money to the other parts of the economy, such as happened to U.S. worker wages.

The translation of why wages relate to energy consumption is simple: by and large workers get paid to do things that directly and indirectly consume energy. Even companies like Google and Facebook don't avoid this. Though most of their revenue comes from selling advertisements, they sell these ads for companies that in turn sell products that are made of resources and consume energy to manufacture and operate. So many businesses of the "information economy" (Google, Facebook, Twitter) are actually supported by the "old economy" that still makes stuff. Plus their web servers must consume electricity to save our photos and deliver streaming video.

The last three chapters have been heavy on data, scientific concepts, and economic theory. The end of this chapter largely marks the end point for introducing new data. The rest of the book further interprets the data shown thus far and puts it into context of economic narratives we hear more in the popular press, outside of formal economic circles.

Chapter 7 now takes a more qualitative approach to summarizing U.S. energy, economic, and political trends. Placing many of the important trends in one location helps show just how many of them each follow three major phases over the last 100 years. This approach also provides context for the perceptions of accessibility to an American middle-class lifestyle, both before and after the 1970s, that most politicians claim, or at least hope, to open up to a larger share of citizens today. Chapter 7 also sets the stage for understanding just how much we have changed, and how much we might be able to change, the size and structure of the U.S. economy.

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