Chapter 2
Accounting for the Wealth of Nations

Essentially, all models are wrong, but some are useful.
[1, p. 424]

—George E. P. Box

The Introduction (Chap. 1) opened with (a) the observation that economic growth has slowed in mature economies of the world and (b) the forecast that growth will remain slow for the foreseeable future. This is seen as a problem because robust economic growth is thought to be a necessary condition for maintaining growth in living standards. The observation and forecast are widely shared among mainstream economic analysts who blame stagnation in the conventional factors of production (manufactured capital, labor, and technology—all endogenous to the economy) for the bleak situation. Proposed solutions to this economic problem include investment in manufactured capital and technology (supply-side policies) or boosting consumption (demand-side policies).

We also presented evidence for an additional, biophysical reason for the slowdown: the economy is tightly coupled to the biosphere, and we are depleting stocks of natural capital, particularly stores of energy. As these natural resources are depleted, they become more expensive to produce, and economic growth suffers. We suggested the startling notion that because standard economic theory does not perceive the slowdown in biophysical terms, the mainstream prescription of investment in manufactured capital could fail as it locks in future demand for natural resources that become ever more expensive to extract. Thus, policy prescriptions based on the conventional wisdom can, unwittingly, exacerbate economic slowdown in the long-term.

How could it be that mainstream, growth-targeted economic policies actually contribute to slowdown? Could it be that the mainstream model is incomplete or ill-suited for the age of resource depletion?

Before exploring these questions, we note that models (economic and otherwise) are informed by metaphors; simplified ways of explaining and framing the world in which we live. Looking back, we note that the Introduction (Chap. 1) contained much metaphorical language.[1] We spoke of "driving" economic growth and of "fueling" the "economic engine." And, we said that the economy has "stalled." Society's

[1] The use of mechanical metaphor language in Chap. 1 was a deliberate decision to bring attention to the dominant metaphors of the day.

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manner of speaking about the economy reveals that the dominant mainstream economic metaphor is mechanical. In this chapter, we explore how a machine metaphor for the economy came to be and suggest that a new metaphor can inform development of national accounting that is appropriate for the age of resource depletion.

2.1 Three Eras

There have been three eras of the relationship between the biosphere and the economy in recent human experience. We will call them the era of abundance, the era of energy constraints, and the age of resource depletion. The era of abundance began with the dawn of the industrial revolution and continued to the oil embargoes of the 1970s;[2] the era of energy constraints covers the time between the oil embargoes and the run-up to the Great Recession;[3] and, today, we are entering the age of resource depletion.[4] Each era is associated with a metaphor that explains the economy, an economic model that guides national accounting, and a macroeconomic production function that describes output (usually measured by GDP). From one era to the next, there is revision and refinement of human understanding of the relationship between the biopshere and the economy. Each revision of understanding is informed by a change in the dominant metaphor that explains the economy. Each transition brings changes in national accounting[5] and modifications to the production function.

Today, we stand at the dawn of the age of resource depletion, and it is an important time to review past eras and anticipate changes ahead. By doing so, we can anticipate some important questions: What new economic metaphors and models are appropriate for the age of resource depletion? How should we now measure and model economic growth? And, what changes should occur in national accounting?

2.1.1 Era of Abundance

The defining characteristic of the era of abundance was plentiful natural resources relative to economic demand.[6] Society had not moved too far along the path foretold

[2] Roughly speaking, 1850–1973, with pauses for the World Wars.

[3] Approximately, 1973–2003.

[4] From 2003 to the present.

[5] In this section, the term "national accounting" does not connote the Systems of National Accounts (SNAs) that are necessilarly financial in nature. Rather, we are using "national accounting" to indicate accounting of a variety of quantities at the national level in both physical as well as financial terms, including energy production and consumption, material extraction rates, and ecosystem services.

[6] It should be noted that there were local examples of resource constraints, such as caused population declines in the Maya [2].

by the best-first principle (Sect. 1.3.2), and materials and energy were easy to obtain from the biosphere. On the global scale, ecosystem services, particularly waste assimilation, were sufficient for the scale of the economy.[7] In this era, the abundance of natural resources made industrialization possible in many economies. The binding economic constraint was the availability of manufactured capital and/or labor. Expanding the stock of capital or the pool of labor generated, to a greater or lesser extent, economic growth.

In the era of abundance, the dominant metaphor for the economy was the "clockwork" mechanism from classical physics. By associating complex phenomena with something simpler and well-understood, all metaphors help us make sense of the world around us, and the clockwork metaphor signaled that the economy was as predictable and regular as time itself.

The traditional model of the economy (Fig. 2.1) was unashamedly mechanistic and was based on classical physics' models of mechanical equilibrium which arose from the "clockwork universe" [5–7]. In the traditional model, goods and services flow from the production sector to the household sector (consumption) in exchange for payments (spending). Factors of production are sold by the household sector to the production sector in exchange for wages and rents (income). Attention is primarily focused on the circular, clock-like flow of money (dashed line).

The traditional model is reflected in the economic production functions that arose in the era of abundance. Economic output (y) was deemed to be a function of the factors of production (manufactured capital, k, and labor, l) and augmenting technology (A) in the Cobb–Douglas equation [9]:

$$y = Ak^{\alpha} l^{\beta}, \tag{2.1}$$

where α is the output elasticity of capital, β is the output elasticity of labor, and $\alpha + \beta = 1$ if constant returns to scale are assumed.[8]

In the era of abundance, the clockwork metaphor, the traditional model, and the Cobb–Douglas production function were all, in some sense, appropriate: capital and labor were the key drivers of economic performance. And, national accounting reflected the binding constraints of the time. Economist Simon Kuznets led the

[7] There are notable *local* exceptions such as the lethal 1952 smog cloud in London, caused by coal-burning power station emissions, that, according to some, claimed as many as 12,000 lives [3, 4]; pollution in the Cuyahoga river and Love Canal; and the legendary smog problems in Los Angeles.

[8] Constant elasticity of substitution (CES) production functions also appeared in this era. CES productions functions have the form

$$y = A\left[\delta_1 k^{\rho} + (1 - \delta_1) l^{\rho}\right]^{\frac{1}{\rho}},$$

where δ_1 is the factor share for capital (k), $\rho \equiv \frac{1}{1-\sigma}$, and σ is the elasticity of substitution between capital (k) and labor (l) [9]. Although the form of the CES model is different from the Cobb–Douglas equation, the functional relationship remains the same: output (y) is a function of manufactured capital (k) and labor (l) only.

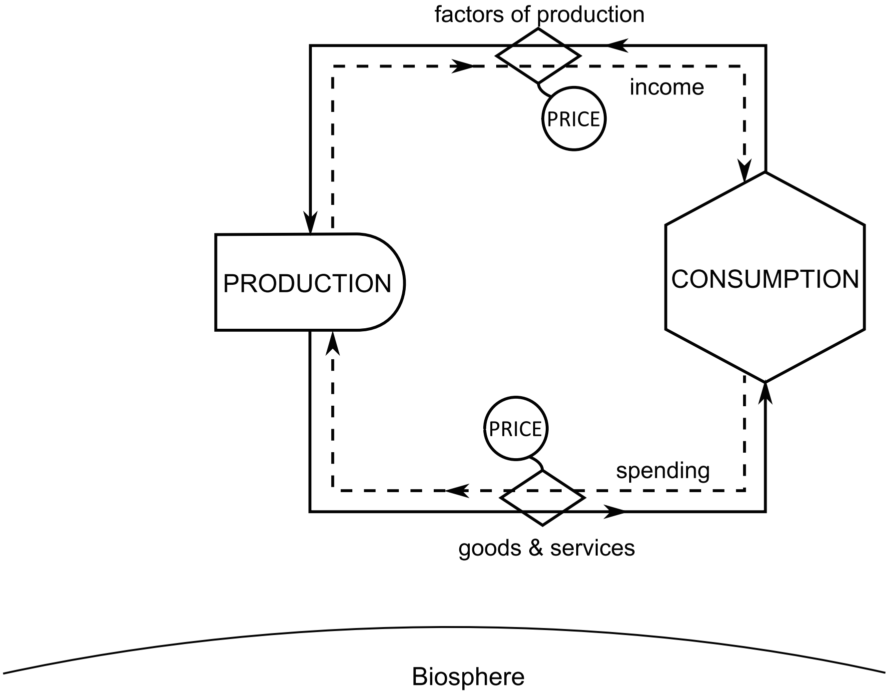

Fig. 2.1 In the traditional economic model, the economy is represented as a circular flow of goods and services between two sectors. Producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers. There are no connections between the economy and the biosphere. We use energy circuit diagrams to represent the flow of materials, energy, and information [8]

development of the first official national accounting tables in response to the extreme unemployment of the Depression. The first US national accounts (published in 1947) were focused primarily on financial quantifications of flows of capital and labor among sectors of the economy.[9] And, they still are.

Today, with the benefit of hindsight, we note that the clockwork metaphor, the traditional model of the economy, and the first US national accounts precluded any sort of connection between the economy and the biosphere.[10] Thus, only the internal dynamics of the economy were important.[11] By implication, the clockwork

[9] Natural resources, including energy, were, and still are, included in Systems of National Accounts as *costs*. They are counted in financial units (dollars and yen), not physical units (barrels, tonnes, and gigajoules).

[10] To this day, the US national accounts still do not include interactions between the economy and the biosphere.

[11] Because Fig. 2.1 has no flow of energy into the economy, we may consider the traditional model of the economy to be a perpetual motion machine of the *first kind*: the economy works without the input of energy, thus violating the first law of thermodynamics—the law of conservation of energy [10].

metaphor and traditional model signaled that natural resources were unimportant, effectively assuming that the biosphere would always provide. If a particular natural resource became scarce, substitution to a different, more-readily-available resource would be made. Wastes were quantitatively unimportant, effectively assuming that the biosphere had infinite assimilative capacity. Economic forces, through prices and market mechanisms, were thought to effectively guide any necessary transition within the economy. With the clockwork metaphor, physical constraints imposed by the biosphere on allocation of resources, distribution of outputs, and scale of the economy were outside the scope of economic discussion [11].

In short, the clockwork metaphor and the traditional model of the economy told us that the clockwork-economy could and would carry on.

But, what happens when availability of manufactured capital and labor are no longer the binding constraints on an economy? The answer arrived with the era of energy constraints.

2.1.2 Era of Energy Constraints

It came as a severe shock to the economic establishment that energy constraints brought about by the oil embargos of the early 1970s wrought such economic havoc [12, p. 3]. The global economy "stalled" due to scarcity of a single, highly-constrained resource relative to demand: fuel. How could it be that economists were taken by surprise?

Looking back, we realize that all metaphors inform our thinking about the real world, but, consequently, they also constrain our ability to frame reality. Erroneously, we can mistake the model-metaphor for reality, and we interact with reality in the same manner as we interact with the abstract objects of our models.[12] Classical physics told us the universe was *like* clockwork, so we began to interact with the universe as if it *really were* clockwork. During the era of abundance, economists, guided by the clockwork metaphor and traditional model, were focused on manufactured capital and labor only; they ignored the physical role that energy plays in the economy.

The defining characteristic of the era of energy constraints was the scarcity, relative to demand, of fossil fuel energy resources, particularly oil (see Sect. 1.3.1.). These energy constraints on western economies were caused not by the depletion of oil reserves but by withholding oil supply for political objectives[13] or other geopolitical events.[14]

[12] This fallacious process is known as *reification*; the making (*facere*, Latin) real of something (*res*, Latin) that is merely an idea. Alfred Whitehead refers to this as *the fallacy of misplaced concreteness* [13].

[13] For example, the October 1973–March 1974 oil embargo against Canada, Japan, the Netherlands, the UK, and the US was a response to the US decision to supply arms to Israel during the Yom Kippur War.

[14] For example, the 1979 Iranian revolution disrupted oil supply.

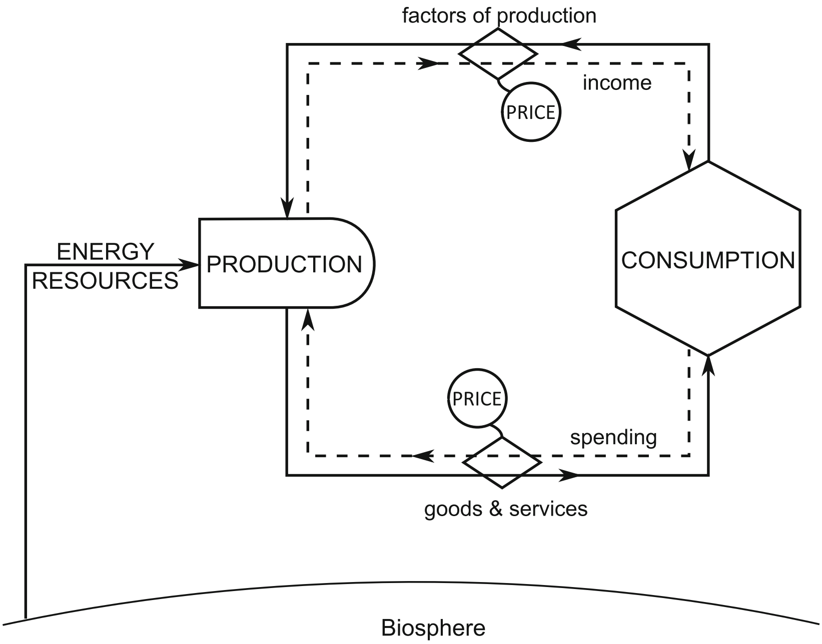

Fig. 2.2 The machine model of the economy includes flows of energy into the economy from the biosphere. This may be considered a perpetual motion machine of the second kind

If they did not already know it, many economists and scientists came to realize that energy was required for successful operation of the economic "engine." Some saw that ignoring energy during the era of abundance had been a mistake! The desire to include energy resources in the economic picture spurred the efforts of early (net) energy analysts [14, 15]. Indeed, Fig. 1.2 can be seen as an early attempt to understand the role that energy plays in the economy. In the process, a machine metaphor and accompanying engine model for the economy rose to prominence.

The engine model (Fig. 2.2) accounts for energy flows from the biosphere to the economy. With the new metaphor, the economy changed from being an *isolated* system (Fig. 2.1) to being a *closed* system (Fig. 2.2).[15] The importance of input energy was acknowledged, but wastes were still missing. And, the biosphere was positioned as the provider of energy resources, the larder and gas station of the economy [16].

[15] An isolated system is one that allows no material or energy transfers across its boundary, for example, a perfectly insulated flask. A closed system is one that allows energy but not materials to cross its boundary, such as a greenhouse. A open system, such as a lake, river or ocean, allows both material and energy transfers across its boundary.

In addition to reevaluating the economic metaphor, some researchers reconsidered the production function.[16] Energy augmentation of the Cobb-Douglas production function took several forms [17, Eq. 1], one of which [18, Eq. 3.10] is

$$y = Ak^{\alpha} l^{\beta} e^{\gamma}, \tag{2.2}$$

where e is energy input to the economy,[17] γ is the output elasticity of energy, and $\alpha+\beta+\gamma = 1$ if constant returns to scale are assumed.[18] In addition, a new production function, the LINear EXponential (LINEX) function, appeared [23, 26, 27].

$$y = Ae \tag{2.3}$$

$$A \equiv \mathrm{e}^{a_0\left[2\left(1-\frac{1}{\rho_k}\right) + c_t\left(\rho_l-1\right)\right]} \tag{2.4}$$

In the LINEX function (Eq. 2.3), energy (e) is *the only* factor of production. $\rho_k \equiv \frac{k}{\frac{1}{2}(l+e)}$ is a measure of capital deepening, and $\rho_l \equiv \frac{l}{e}$ describes the increase of labor (l) relative to energy (e). When either ρ_k or ρ_l increases, the only factor of production (energy, e) is augmented (A). a_0 and c_t are fitting parameters, and e in Eq. 2.4 is the exponential function.

In the era of energy constraints, the machine metaphor, the engine model, and energy-augmented production functions were, arguably, apt for their time: energy *was* the binding constraint on the economy. The appearance of energy in the engine model and energy-augmented production functions (Eqs. 2.2 and 2.3) was mirrored by international efforts to include energy in national accounting.[19] The International Energy Agency (IEA) "was founded in response to the 1973/4 oil crisis in order to help countries co-ordinate a collective response to major disruptions in oil supply" [28]. One of the primary objectives of the IEA was "to operate a permanent information system on the international oil market" [28]. Today, that "permanent information system" [29] remains one of the most important sources of economy-level energy production and consumption statistics in physical units.[20] And, the IEA's annual

[16] It must be said that the effort to include energy as anything other than a cost of production remains outside the economic mainstream even today.

[17] There is debate in the literature about quantification of energy input to the economy (e). Most researchers use the thermal equivalent of primary energy [19–22]. Others use useful work obtained by efficiencies from primary exergy [23].

[18] The Constant Elasticity of Substitution (CES) production function can be augmented with energy in several ways, depending upon the desired nesting of energy (e) relative to the other factors of production (capital, k, and labor, l) [24, 25]. Three options exist, but a common approach is:

$$y = A\left\{\delta\left[\delta_1 k^{-\rho_1} + (1-\delta_1) l^{-\rho_1}\right]^{\rho/\rho_1} + (1-\delta)e^{-\rho}\right\}^{-1/\rho}.$$

[19] Again, we are using the term "national accounting" not in the sense of SNA but rather in the sense of data collected at the national level.

[20] As opposed to financial units (currency). Physical units include barrels of oil, tonnes of coal, and gigajoule energy values.

World Energy Outlook series [30] is one of the premier sources of forward-looking analysis on the relationship between energy and the economy. Although physical energy statistics and indicators were not inserted into SNA, the dawn of the era of energy constraints provided the impetus for gathering and disseminating the world's energy data.

Today, with the benefit of hindsight, we note that the machine metaphor and the engine model of the economy continued to ignore the flow of wastes from the economy to the biosphere; the engine model still assumed that the biosphere had infinite assimilative capacity. But, according to the second law of thermodynamics, all real-world processes involve the generation of entropy manifest as the degradation of material and, especially, energy resources.[21] High quality (low entropy) material and energy come in; low quality (high entropy) material and energy go out. Wastes exist! Because the generation of high entropy (low quality) output is a necessary feature of all processes (including economic processes), the generation of wastes is a normal feature of the economy, not an anomaly. The engine model had it wrong.

Furthermore, we see that the machine metaphor and the engine model of the economy were adopted in an era where scarcity of oil supply relative to demand was caused not by the issues associated with the best-first principle (Sect. 1.3.2), but rather by politically-motivated withholding of supply or other geopolitical events. The forward-looking projections from the IEA (and other organizations) continued to assume that there were effectively no physical limitations to increasing the rate of fossil fuel extraction from the biosphere. The presence of natural capital (e.g., oil) was acknowledged, but the quantity of natural capital (e.g., oil remaining underground) was not thought to constrain the extraction rate. In that era, neither the machine metaphor nor engine model deemed that the effects of the best-first principle were a factor in economic performance.

In short, the machine metaphor and the engine model of the economy told us that the engine-economy could and would carry on, so long as it was supplied with energy.

But, what happens when the availability of natural resources, especially energy, is no longer merely a political matter? What happens when stocks of natural resources especially energy, are depleted to such an extent that it becomes too expensive for the economy to obtain them?

The answer arrived with the age of resource depletion.

[21] The depiction of the economy in Fig. 2.2 can be classified as a perpetual motion machine of the second kind: it perfectly converts energy resources into useful output without generating any entropy, in violation of the second law of thermodynamics.

2.1.3 *Age of Resource Depletion*

Much of Chap. 1 was spent describing the age of resource depletion, whose defining characteristic is that stocks of natural capital constrain economic growth. The effects of the best-first principle (exemplified by decreasing $EROI_{soc}$ for oil) and the limited waste-assimilation capacity of the biosphere relative to the disposal rate of materials are now affecting the economy in ways they never did before. Richard England puts it this way:

> [T]here must arrive a moment in the world's history when natural capital is no longer relatively abundant and human-made [manufactured] capital is no longer relatively scarce. At that moment, aggregate output is no longer constrained by the populations of humans [labor] and their artifacts [manufactured capital] and by the productivity of human effort [A in Equations 2.1 and 2.2]. Rather, the scale of economic activity is constrained by the remaining stock of natural capital and by its productivity. . . . When this moment arrives, a new era of history has begun. [31, p. 430]

Prior to the age of resource depletion, mainstream economists assumed that the ability to increase the rates of extraction of natural capital was not a factor in economic growth. They assumed that the biosphere had infinite assimilative capacity for the physical waste of an economy. But, things have changed. As Richard England said (and we echoed at the end of Sect. 1.4), "a new era of history has begun."

When society transitioned from the era of abundance to the era of energy constraints, three important events occurred. (1) The dominant economic metaphor was reevaluated, and the clockwork metaphor and traditional model (Fig. 2.1) were replaced by the machine metaphor and the engine model (Fig. 2.2). (2) The production function was modified to include energy as a factor of production. And, (3) national accounting changed: energy indicators and statistics in physical units were collected and disseminated for all countries.

All of which raises the question, how should the transition from the era of energy constraints to the age of resource depletion affect (1) society's dominant metaphors for and models of the economy, (2) the production function, and (3) national accounting? In the next section (2.2), we present a new metaphor, and the heart of this book (Chaps. 3–7) provides theoretical grounding for national accounting in the age of resource depletion. The way forward on production functions is beyond the scope of this text.[22]

[22] See England [31] for a starting point.

2.2 The Economy is Society's Metabolism

In our opinion (and that of several others[23]) an apt metaphor for the economy in the age of resource depletion should provide for robust interaction and suggest tight coupling between the biosphere and the economy. Specifically, it should account for the following facts about real economies. Economies:

1. intake material and energy from the biosphere;
2. exchange materials, energy, and information internally;
3. discharge material and energy wastes to the biosphere;
4. are affected by energetic costs;
5. are affected nonlinearly by scarcity in the face of low substitutability;
6. can change nonlinearly or in discrete steps with the potential for structural transformation;
7. accumulate embodied energy in material stocks; and
8. maintain organizational structure despite changes in their environment.[24]

Metabolisms[25] exhibit the characteristics in the list above. Metabolisms and the organisms they support are intimately connected with the biosphere: they withdraw materials and energy from the biosphere (1), transfer materials and energy internally via metabolic processes (2), and discharge wastes back to the biosphere (3); in fact, their very survival depends on these processes. Extending Figs. 2.1 and 2.2 to include the facts in items (1)–(3), we obtain Fig. 2.3. Metabolisms are affected by energetic costs (4): an organism that acquires less energy than it expends is doomed. Withholding life-sustaining resources brings drastic, nonlinear consequences for any metabolism (5). Metabolisms enable nonlinear, structural transformations in their host organisms (e.g., metamorphosis, puberty, and evolution) (6). And, energy absorbed by a metabolism is considered to be "embodied" in the cells of the organism (7). Metabolisms exist in a state of dynamic stability (8), adjusting and readjusting to maintain their internal conditions despite changes in the environment; for a metabolism, equilibrium means death! The economy is society's metabolism.

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[23] An incomplete list of authors who are either (a) progenitors for or (b) directly associated with the metabolism metaphor includes Georgescu-Roegen [32], Odum [33], Daly [34], and Hall [35], Heijman [36], Haberl [37], Fischer-Kowalski [38], Liu and Hanauer [39], and Giampietro [40].

[24] We note that several areas of the literature speak to the items in this list. Materials flow analysis (MFA) and economy-wide materials flow analysis (EW-MFA) stress the importance of material intake by the economy. (see Sect. 3.5.) The input–output (I–O) method highlights the effects of internal exchanges of material and information with economies. (see Chap. 7.) Life-cycle assessment (LCA) techniques focus attention on otherwise-neglected wastes. (see Sect.7.8.) Net energy analysis (NEA) predicts that energy resource scarcity reduces energy return on investment (EROI) and sincreases energy prices. (see Sects. 1.5 and 4.3.) The energy input–output (EI–O) method gives prominence to energetic costs of internal material and energy flows. (see Chap. 7.) And, thermodynamic control-volume modeling describes transient behavior and system transformations. (see Chaps. 3–6.)

[25] The Greek root of metabolism (*metabolē*) means "change."

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