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Beyond GDP

National accounting in the age of resource depletion

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Contents

Chapter 2
Accounting for the wealth of nations

A motto. [1, p. 26]

—Wendell Berry

The Introduction (Chapter 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 factors of production (manufactured capital, labor, and technology) 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 (Chapter 1) contaied 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 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

[1] This was deliberate decision to bring attention to the dominant metaphors of the day.

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'll 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 runup 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 an economic production function that describes output (usually measured by GDP). From one era to the next, there is revision and refinement of the 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. Society had not moved too far along the path foretold by the Best-First Principle (Section 1.4.2), 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.[6] In this era, the

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[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're 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] 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 [2, 3]; pollution in the Cuyahoga river and Love Canal; and the legendary smog problems in Los Angeles.

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 (Figure 2.1) was unashamedly mechanistic and was based on classical physics' models of mechanical equilibrium which arose from the "clockwork universe" metaphor.[4–6] 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).

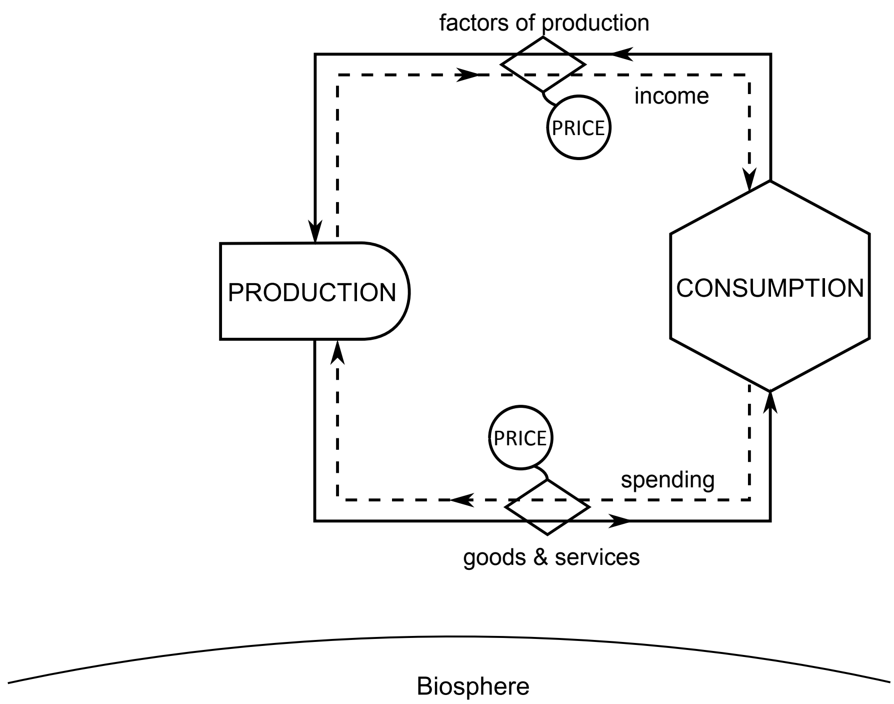

Fig. 2.1 In the traditional model, the economy is represented as a circular flow of goods and services between two sectors. Producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers. We use energy circuit diagrams to represent the flow of materials, energy and information.[7]

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 [8]:

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

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.[7]

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

Today, with the benefit of hindsight, we note that the clockwork metaphor and the traditional model of the economy precluded any sort of connection between the economy and the biosphere. Thus, only the internal dynamics of the economy were important.[9] By implication, the clockwork 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]

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[7] 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).[8] 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.

[8] 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).

[9] Because Figure 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]

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.[10] 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 Section 1.4.1.) These energy constraints on western economies were caused not by the depletion of oil reserves but by withholding oil supply for political objectives[11] or other geopolitical events.[12]

If they didn't 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, Figure 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 (Figure 2.2) accounts for energy flows from the biosphere to the economy. With the new metaphor, the economy changed from being an *isolated*

[10] 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]

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

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

system (Figure 2.1) to being a *closed* system (Figure 2.2). 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]

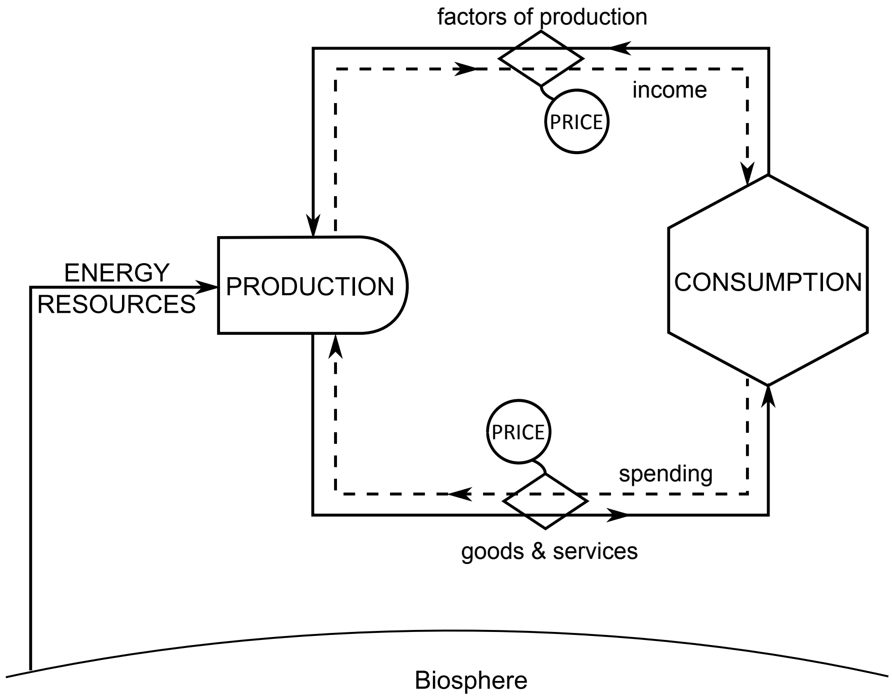

Fig. 2.2 The machine model of the economy includes flows of energy into the economy from the biosphere. This may be considered a perpetual motion machine of the second kind.

In addition to re-evaluating the economic metaphor, some researchers reconsidered the production function.[13] Energy augmentation of the Cobb-Douglas production function took several forms [17, Equation 1], one of which [18, Equation 3.10] is

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

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

where e is energy input to the economy,[14] γ is the output elasticity of energy, and $\alpha+\beta+\gamma=1$ if constant returns to scale are assumed.[15] In addition, a new production function, the LINear EXponential (LINEX) function, appeared.[23, 26, 27]

$$y = A\, e\, ;\; A \equiv \mathrm{e}^{a_0\left[2\left(1-\frac{1}{\rho_k}\right)+c_t\left(\rho_l-1\right)\right]} \tag{2.3}$$

In the LINEX function, energy (e) is *the only* factor of production. $\rho_k \equiv \frac{k}{1/2\,(l+e)}$ 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, A increases. a_0 and c_t are fitting parameters, and e 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 (Equations 2.2 and 2.3) was mirrored by international efforts to include energy in national accounting.[16] 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.[17] And, the IEA's annual 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 Systems of National Accounts, 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

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[14] 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]

[15] 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 the a common approach is:

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

[16] Again, we are using the term "national accounting" not in the sense of Systems of National Accounts but rather in the sense that data needs to be collected at the national level.

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

of material and, especially, energy resources.[18] 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 (Section 1.4.2), 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 was acknowledged, but the quantity of natural capital 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.

2.1.3 Age of resource depletion

Much of Chapter 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]

[18] The depiction of the economy in Figure 2.2 can be classified as a perpetual motion machine of the second kind: it perfectly converts energy resources into work (useful energy services) without generating any entropy, in violation of the Second Law of Thermodynamics.

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. Or, as we said at the end of Section 1.5, this is the end of an era.

When society transitioned from the era of abundance to the era of energy constraints, three important events occurred. (1) The dominant economic metaphor was re-evaluated, and the clockwork metaphor and traditional model (Figure 2.1) were replaced by the machine metaphor and the engine model (Figure 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 (Chapters 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.[19]

2.2 The economy is society's metabolism

In our opinion, 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 non-linearly by scarcity in the face of low substitutibility
6. can change non-linearly 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.[20]

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

[20] We note that several areas of the literature speak to the items in this list. Materials Flow Analysis (MFA) and Economy-Wide Materials Flow Analys (EW-MFA) stress the importance of material intake by the economy. (See Section 3.5.) The Input-Output (I-O) method highlights the effects of internal exchanges of material and information with economies. (See Chapter 7.) Life-Cycle Assessment (LCA) techniques focus attention on otherwise-neglected wastes. (See Section 7.6.) Net Energy Analysis (NEA) predicts that energy resource scarcity reduces Energy Return on Investment (EROI) and increases energy prices. (See Sections 4.3 and 9.4.) The Energy

Metabolisms[21] 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 Figures 2.1 and 2.2 to include the facts in items (1)–(3), we obtain Figure 2.3. Metabolisms are affected by energetic costs (4): an organism that obtains less energy than it expends is doomed. Withholding life-sustaining resources brings drastic, non-linear consequences for any metabolism (5). Metabolisms enable non-linear, 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.

Although we're not the first to suggest the metabolism metaphor for the economy [32–37], we believe that the metabolism metaphor is underutilized on both practical and theoretical levels. On the practical level, the metabolism metaphor is underutilized because Systems of National Accounts, to date, is built upon the clockwork metaphor and traditional model for the economy (Section 2.1.2). This book attempts to correct that oversight by using the metabolism metaphor to develop a rigorous theoretical framework for comprehensive national accounting. (See Chapters 3–7.) On a theoretical level, the metabolism metaphor is underutilized, because most researchers (with the exception of Giampietro [33, 34]) use the metabolism metaphor merely as as framing device for analyses of raw material flows into the economy for the purpose of understanding stocks of raw materials in the biosphere.[22] Those who employ the metabolism metaphor tend to focus little attention on capital stock within the economy itself. In effect, this is the same oversight as national accounting: under-appreciation of the important role of capital in determining material and energy

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Input-Output (EI-O) method gives prominence to energetic costs of internal material and energy flows. (See Chapter 7.) And, thermodynamic control-volume modeling describes transient behavior and system transformations. (See Chapters 3–6.)

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

[22] The field most closely associated with the metabolism metaphor is Materials Flow Analysis (MFA). To be fair, materials flow analysts clearly acknowledge that materials flow into the economy (minerals and ores, especially), in part, for the purpose of building up stocks of technical infrastructure (buildings), livestock, and people.[35, p. 116] However, there is little emphasis on quantifying *levels* of material stock in Materials *Flow* Analysis, as its name implies. In fact, the equations in MFA [35, Equation 1] are almost always written as

$$\text{inflow} = \text{outflow} + \text{accumulation} ,$$

reflecting the focus on material inflow to the economy. In this book, similar equations (see Equation 3.2) are written as

$$\text{accumulation} = \text{inflow} - \text{outflow} ,$$

thereby focusing on accumulation of stocks within the economy.

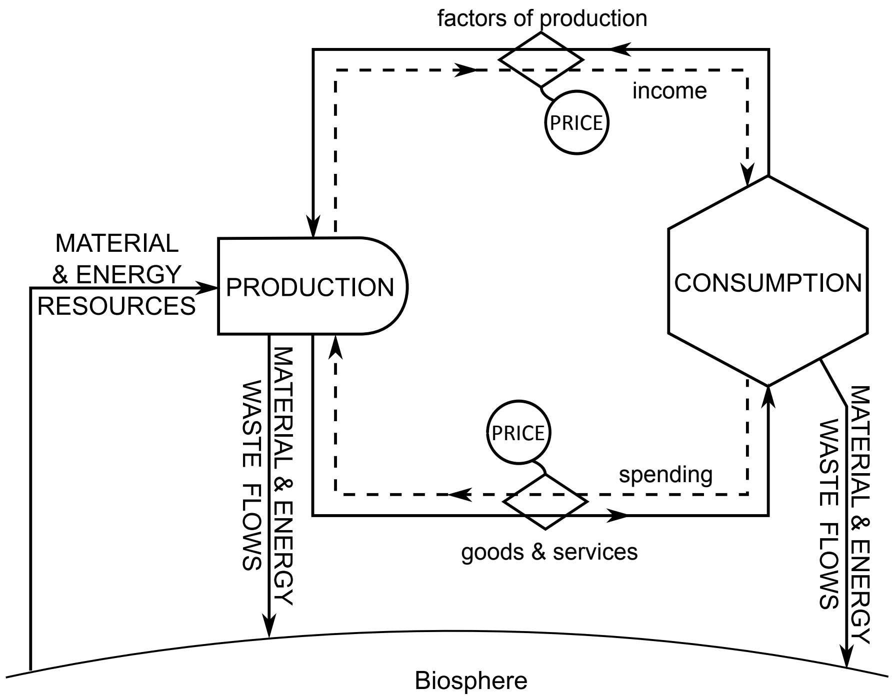

Fig. 2.3 The metabolism model provides a comprehensive view of the economy, fully consistent with the laws of thermodynamics, including degraded resources (waste) expelled to the environment as a necessary consequence of economic activity.

demand for the emplacement, use, maintenance, and replacement of the very same capital.

It becomes a vicious cycle. By not accounting for capital stock on a physical basis in national accounting, society is unable to appreciate the important physical role that capital stock plays in the economy (Section 1.4.3). Because society under-appreciates the physical role of capital stock in the economy, there is little urgency to begin accounting for manufactured capital on a physical (rather than financial) basis.

We think that a deeper understanding of the metabolic metaphor can serve to both highlight the important physical role of manufactured capital stock and provide the basis for a rigorous theoretical framework for comprehensive national accounting. In the following sections, we deepen the metabolism metaphor by considering anabolism (capital formation), catabolism (energy production), autophagy (recycling), and issues of scale. Thereafter, we summarize the benefits of the metabolism metaphor for national accounting.

2.2.1 Anabolism (capital formation)

Metabolic processes are classified as anabolic and catabolic (Section 2.2.2). Anabolic processes build up materials within the body (bones, muscles, tissues). For example, anabolic steroids are hormones that stimulate the human body's natural muscle and bone growth processes. Anabolic processes are fueled by the breakdown of adenosine triphosphate (ATP), the cellular energy source. Raw materials for anabolic processes are provided by food, which, ultimately, comes from the biosphere.

The economic analog to biological anabolism is capital formation, net addition to the stock of capital within a period of time. Traditionally, capital formation is measured in currency units. Thus, capital formation is the financial evidence of the emplacement of manufactured infrastructure. Whereas biological anabolism is fueled by ATP, capital formation is fueled by the energy sector of the economy. The raw material for capital formation comes to the economy from the biosphere.

We discuss extraction and use of materials in Chapter 3 and the importance of capital stock throughout the book.

2.2.2 Catabolism (energy production)

Catabolic processes break down and destroy material stocks within an organism through an oxidation process. At the cellular level, catabolic oxidation releases chemical free energy, some of which synthesizes adenosine triphosphate (ATP), thereby providing fuel to cells. The rest of the released energy is manifest as waste heat. One of the waste products of cellular catabolism is CO_2.

The analogy between catabolic processes and the work of the energy sector in the economy is striking. Power plants (fired by coal, oil, and natural gas) break down fossil fuels in an oxidation process (combustion) to produce useful energy (typically, electricity or mechanical drive [23]), thereby providing energy to other sectors of the economy. Both waste heat and CO_2 are byproducts of combustion, and O_2 is consumed in the process.

We focus on energy production in the economic context in Chapter 4.

2.2.3 Autophagy (recycling)

One catabolic pathway, autophagy, involves the breakdown of damaged, unneeded, or dysfunctional cellular components (proteins and cell organelles) for the purpose of re-use within the organism. Autophagy can be an adaptive response to low calorie intake, promoting cell survival.

Again, the analogy between cellular metabolism and the economy is striking. Whereas cellular autophagy repurposes proteins and cell organelles for re-use by an organism, recycling repurposes degraded yet economically-valuable materials for re-use by the economy. Furthermore, recycling can also be an adaptive response to reduced material and energy inputs. One famous example can be found on the streets of Cuba. In the face of economic sanctions, government restrictions on vehicle purchases, and high import tariffs, automobile imports by Cuba are very low. As a result, Cuba hyper-recycles autos that were imported prior to sanctions and manufactures replacement parts locally. The average lifespan of automobiles has been extended such that an estimated 60,000, pre-1960 cars [38] (so-called "yank tanks") are in service on the island.[23] (See Figure 2.4.)

Fig. 2.4 Vintage autos ("yank tanks") in Cuba (2011).
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`http://lcowlesphotography.wordpress.com/2011/02/13/old-cars-of-cuba/`.
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`http://ocean.otr.usm.edu/~w301497/travels/cuba2010/cuba2010b.html`
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It's not difficult to imagine that dynamics similar to Cuba's will emerge if the inflow rate of any important natural but recyclable resource is reduced to a trickle by the effects of depletion.[24]

Regardless of the origin of material constraints, the effect on the economy will be the same: re-use, recycling, and, where possible, substitution to other resources will become increasingly imperative.

We focus on recycling in Section 8.4.

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[23] Despite the recent change allowing new car purchases by individuals, astronomical import taxes mean that Cuban streets remain populated with vintage 1950s autos.[39]

[24] See Section 1.4.2 for a discussion of depletion of a non-recyclable natural resource, oil.

2.2.4 Issues of scale

The metabolism metaphor brings to light issues of scale (size) for economies and societies. First, scale is directly related to material flow rates. Larger organisms consume food at higher rates, in part to obtain essential nutrients to replenish cellular structures. Similarly, economies with higher levels of emplaced capital require larger material flow rates to provide raw materials to machines and food to people. (See Section 1.4.3 for more on this topic.)

In Figure 2.5, we see Max Kleiber's empirically-determined relationship between metabolic rate (heat production, in kcal/day) and animal mass (in kg) plotted on a log-log scale for a variety of animals, from mice to whales. Green dots show data points, and lines represent theoretical scaling due to either mass (weight) or surface area. The best fit to the data (red line) passes between the weight and surface area lines.

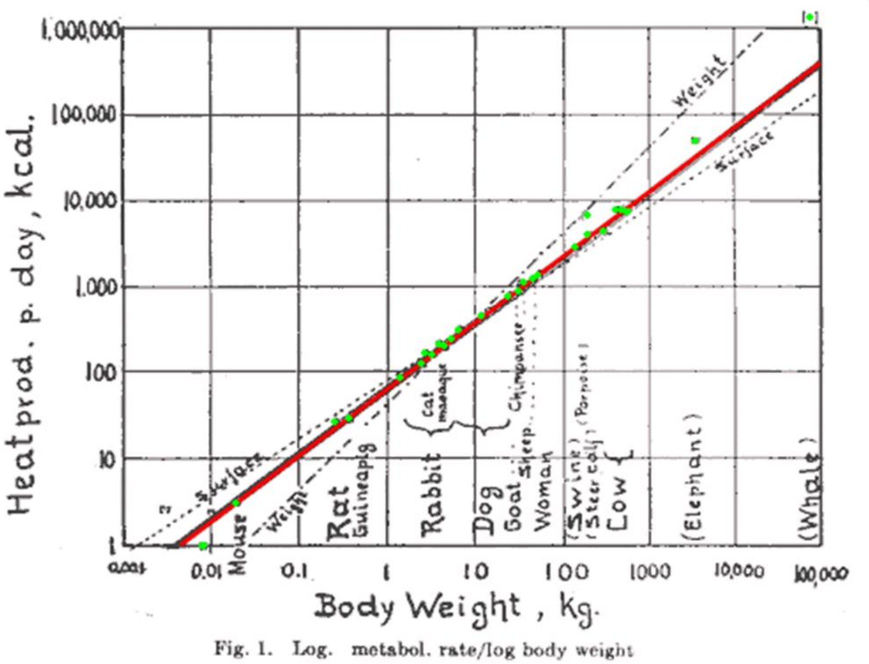

Fig. 2.5 Kleiber's law for metabolic rates (heat production) of different-sized animals [40, p.530]. Larger animals, as determined by mass, have a higher metabolic rate, but the relationship between mass and metabolic rate is not linear.
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Kleiber's law which states this relationship mathematically, is defined as

$$\dot{Q} = q_0 m^{3/4} \tag{2.4}$$

where $\dot{Q}$ is metabolic rate (heat production), m is the mass of the animal, and q_0 is a mass-independent normalization constant. From Equation 2.4, we see that doubling the mass increases the metabolic rate by $2^{3/4} = 1.68$ times. To compensate for higher rates of heat loss due to high surface area-to-volume ratio, small animals have proportionally higher metabolic rates and proportionally larger food requirements.

If the economy is society's metabolism and the scale of an organism corresponds to the inventory of capital stock in an economy, the metabolism metaphor suggests that larger economies will require a higher rate of energy supply. In fact, we know this to be true. Built-out, industrialized economies with higher levels of emplaced capital (those with more roads, cars, and buildings) tend to consume energy at a higher rate, both in an absolute sense and on a per-capita basis, compared to developing economies.

2.2.5 Benefits of the metabolism metaphor

The metabolism metaphor is compelling, because it helps us to see more clearly and understand more deeply how the real economy operates. But does the metabolism metaphor lead us to a better understanding of the coupling between the biosphere and the economy and provide guidance for more-comprehensive national accounting? We think so.

In terms of a better understanding of the economy, the metabolism metaphor teaches us that the economy is a biophysical entity that requires both materials and energy for survival. We learn that economic activity is *natural*. It can be likened to breathing (respiration): O_2 is consumed as CO_2 is produced. It can be likened to digestion: raw materials and chemical potential energy are ingested, the body grows, and energy is provided for everyday activities. Just as food from the biosphere provides materials and energy for anabolic and catabolic processes in an organism, materials and fuels from the biosphere provide matter and energy for capital formation and energy production in society. Without materials and energy from the biosphere, metabolisms fail and organisms die. Without materials and energy from the biosphere, the economies collapse and societies fade away. In short, the economy is coupled to the biosphere, because it is utterly and completely dependent upon it.

The metabolism metaphor teaches us that larger economies demand increasingly higher material and energy flow rates from the biosphere. We see that limits to economic growth are both possible and expected. From the metaphor we learn that economic "stall" is not pathological, but natural, especially in mature economies that have encountered some type of biophysical limit. (See Section 1.4.2.) We might expect to encounter any number of limits: supply rates of materials from the biosphere, supply rates of energy from the biosphere, scale of the economy relative to the biosphere. In the metabolism metaphor, autophagy indicates that stocks of capital within society are reservoirs of material and (embodied) energy that can and should be broken down and re-used or re-purposed, rather than discarded, when out of service.

Through an understanding of the deep interconnectedness and complexity of organisms and species in the biosphere, we come to appreciate the interdependence among actors within and sectors of the economy. Furthermore, an appreciation of the complex nature of economies leads us to acknowledge the difficulty in discerning precisely which limit(s) is (are) encountered when growth stalls. In fact, there is no single explanation for the slowdown of growth in OECD economies discussed in Section 1.1. The best explanation to date involves many intertwining factors: slowing growth of energy input rate, decreasing energy return on investment in the liquid fuel sector, problems in the credit markets, etc.

In terms of national accounting, a deeper understanding of the metabolism metaphor will lead to significant changes in national accounting. It will lead us to acknowledge the important role of *both* flows (e.g., GDP, rates of material and energy extraction from the bioshere, rates at which money spins through the economy) *and* stocks (e.g., manufactured capital, monetary savings, non-renewable energy supplies). Furthermore, appreciation of the physical basis of the real economy will lead us to account for both stocks and flows in physical units (kg and kJ) as well as financial units (currency).

Deeper understanding of the metabolic metaphor will lead systems of national accounts to become focused as much on stocks as on flows. Systems of national accounts will expand beyond financial accounting to become a compendia of both physical as well as financial assets of an economy. By counting flows *and* stocks in both physical and monetary units, national accounting will provide a comprehensive picture of both the *health* and the *wealth* of economies, respectively.

2.3 New national accounting

Society needs to respond to the material and energy shortages that we now face (Chapter 1), and part of that response should involve more-comprehensive national accounting guided by a deeper understanding of the real economy gained through the metabolism metaphor (Section 2.2). It is imperative that we begin now to help society deal with impending biophysical limits.

But how? What should we be counting and in what units? And, how should the data be analyzed?

As discussed in the Prologue, the UN System of Environmental-Economic Accouting (SEEA) is a conceptual framework that was developed by a wide range of experts beginning in the early 1990s. This framework has just undergone a third, thorough revision using a global collaborative process. The SEEA are national accounts that capture data related to “interactions between the economy and the environment, and the stocks and changes in stocks of environmental assets.”[9, p. 1] These accounts measure physical as well as financial flows, and are designed to dovetail with the SNA. As such, the UN SEEA represents the state of the art, in terms of accounting material and energy resource flows through our economies. Using the system allows national governments to answer questions that were previously unknown, such as, "How much steel do we currently use?" or "How much concrete is embodied within our economy?" Indeed, similar analyses as presented in Figure 1.2 (GDP vs. as a function of fuel consumption) might be undertaken for any material (e.g., iron or water) tracked by the SEEA. Governments gain a great deal of understanding about the energetic and material requirements of the country through the use of SEEA.

Because the SEEA framework is defined at the economy-wide (E-W) scale, there are many more important questions that still cannot be answered. One such question is, "What are the material and energetic requirements to scale up the renewable energy industry?" This is a highly important question for future sustainable development, not just for nations, but for the globe as a whole. Such an analysis would require measuring inter-sectoral (i.e., intra-economy) flows of materials and energy. In the age of resource depletion, we believe obtaining inter-sectoral flows to be an essential extension of the UN SEEA.

Firm theoretical grounding is needed *before* we begin the process of expanding national accounts. We need a framework, a way to organize our thoughts about the notion of national accounting in the age of resource depletion. This book is an attempt to provide just that: a theoretical framework for comprehensive national accounting in the age of resource depletion that could be adopted in systems of national accounts.

The first question above ("What should we be counting and in what units?") is the topic for the remainder of this section, and the answer provides the structure for the heart of the book. The second question above ("How should the data be analyzed?") is the topic of Chapter 7.

We believe the key to understanding society's metabolism in the age of resource depletion is to understand how materials, energy, embodied energy, and economic value each interacts with the economy. Specifically, it is important to understand how each accumulates within the economy and how each flows into, within, and out of the economy. The first three items (materials, energy, and embodied energy) are inspired directly by the metabolism metaphor. The fourth item (economic value) is necessary to understand the way that the lifeblood of economies (currency) flows through the economy. Of course, each of the items in the list interacts with the others and the biosphere dynamically. If we can begin to carefully track these items, we will be on our way toward gathering the information necessary to improve national accounting for the age of resource depletion.

Systems of national accounts that are informed by the metabolism metaphor and account for materials, energy, embodied energy, and economic value may allow consumers, producers, and policy-makers to answer critical questions that are not answerable today, such as:

1. **How much energy was used in the manufacture and transport of two competing goods in the supermarket?** (Or, equivalently, how much energy is embodied in two competing goods in the supermarket?)
2. **What might be the optimal scale of an economy in terms of GDP and what are the impacts of an optimally-sized economy on natural capital?**
3. **How is scarce fossil fuel dependency embedded in the interlocking fabric of the economy?**

4. **How will economies that are dependent on coal, oil, and other forms of non-renewable energy transition to renewable forms of energy?**
5. **How might an economy be affected as an increasing share of production is directed toward replacing degraded ecosystem services?** [41, p. 221]
6. **What are the material and energy requirements to scale up the renewable energy industry?**

Our approach to developing a rigorous theoretical foundation for comprehensive national accounting is to develop a dynamic model by applying rigorous thermodynamics to materials and energy flows into, among, and out of economic sectors, informed by the metabolism metaphor, in a manner that is verifiable against the existing (or expanded) national accounts.

2.4 Structure of the book

The list of items to be accounted (materials, energy, embodied energy, and economic value) provides structure for our proposed framework and much of the rest of this book.

Part I addresses flows of physical matter and energy through the economy. Chapter 3 discusses material flows and accumulation. Flows of energy are covered in Chapter 4, and a rigorous, thermodynamics-based definition of and accounting for embodied energy is presented in Chapter 5.

In Part II, we turn to flow and accumulation of non-physical entities through the economy. Flows and accumulation of economic value are discussed in Chapter 6. In Chapter 7, we combine the results from Chapters 5 and 6 to develop an important indicator of economic activity: the energy intensity of economic production.

Part III gives context to the framework developed in Parts I and II. Chapter 8 draws out some of the direct implications of our model. Chapter 9 looks at unfinished business: practical, conceptual, and theoretical issues that arise in the development of our new model. And, we end with a summary in Chapter 10.

Throughout the methodological chapters (3–7), our accounting framework is developed through a series of increasingly-disaggregated models of the economy (Table 2.1), and we use the US auto industry as a running example for application and discussion.

Table 2.1 Examples used throughout this book.

Example	Sector 0	Sector 1	Sector 2	Sector 3
A	Biosphere	Society	NA	NA
B	Biosphere	Final Consumption	Production	NA
C	Biosphere	Final Consumption	Energy	Goods & Services

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