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Accounting for the Environment

A Thermodynamic Approach to Energy and the Future Economy

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Roman

a	stock of apples [-]
a	input output ratio, mixed units
$\dot{a}$	apple flow rate [apples/s]
$\mathbf{A}$	input output matrix, mixed units
B	ecosystem biomass stock [kg]
B	embodied energy [MJ]
$\dot{B}$	embodied energy flow rate [MJ/year]
$\mathbf{B}_K$	column vector of energy embodied in capital stock [MJ]
$\mathbf{B}_{\dot{W}}$	column vector of waste flows [MJ/year]
E	direct energy [MJ]
$\dot{E}$	direct energy flow rate [MJ/year]
$\mathbf{E}_0$	column vector of direct energy inputs from the biosphere [MJ/year]
K	mass of capital goods [kg]
$\dot{K}$	capital goods mass flow rate [kg/year]
n	number of sectors in the economy
p	a system property
P	ecosystem photosynthetic energy production rate [J/year]
P	mass of products [kg]
$\dot{P}$	product mass flow rate [kg]
$\dot{Q}$	waste heat flow rate [MJ/year]
R	mass of resource [kg]
$\dot{R}$	mass flow rate of resources [kg/year]
s	stock of steel [kg]
$\dot{s}$	mass flow rate of steel [kg/year]
S	mass of short-lived goods [kg]
$\dot{S}$	mass flow rate of short-lived goods [kg/year]
t	time [year]

T	total energy [MJ]
$\dot{T}$	total energy flow rate [MJ/year]
$\mathbf{T}_1$	column vector of total energy flows ($\dot{T}$) from society to the economy [MJ/year]
$\dot{W}$	waste flow rate [kg/year]
X	stock of economic value [$]
$\dot{X}$	economic value flow rate, mixed units
$\mathbf{X}_t$	transaction matrix [$/year]
$\hat{\mathbf{X}}$	diagonal matrix of sector outputs in mixed units [$/year or MJ/year]

Greek

α	ratio of inflowing capital stock rate to capital stock [1/year]
δ_{ij}	Kronecker delta
ε	energy intensity [MJ/$]
$\boldsymbol{\varepsilon}$	column vector of sector energy intensities [MJ/$]
$\eta_{\dot{R}}$	resource efficiency [kg/kg]
γ	depreciation rate [1/year]
$\hat{\boldsymbol{\gamma}}$	diagonal matrix of depreciation rates [1/year]
$\rho_{\dot{S}}$	ratio of short-lived material flow rate to resource flow rate [kg/kg]

Subscripts

0	Biosphere
1	Society (Example A) or Final Consumption (Examples B and C)
2	Production sector (Example B) or Energy sector (Example C)
3	Goods and Services sector (Example C)
B	pertaining to embodied energy
$dest$	destruction
gen	generation
i	economic sector index
in	inflow
j	economic sector index
k	economic sector index
K	pertaining to capital stock
out	outflow
t	transaction
$waste$	pertaining to waste

Preface

It was six men of Indostan
To learning much inclined,
Who went to see the Elephant
(Though all of them were blind),
That each by observation
Might satisfy his mind.

⋮

And so these men of Indostan
Disputed loud and long,
Each in his own opinion
Exceeding stiff and strong,
Though each was partly in the right,
And all were in the wrong!

Moral.

So oft in theologic wars
The disputants, I ween,
Rail on in utter ignorance
Of what each other mean,
And prate about an Elephant
Not one of them has seen!
[1, p. 259–261]

— John Godfrey Saxe

The vast majority of physical scientists are concerned that quality of life may very well decrease in the future. We are encountering limits to the rates at which natural resources can be extracted, limits for the rate at which wastes (including anthropogenic carbon emissions) can be assimilated by the biosphere, and limited options for human ingenuity to substitute for depleted natural capital and diminished ecosystem capacity. Because of these factors, the future health and viability of all economies are at risk.[2] Conversely, the vast majority of economists and policy-makers predict that quality of life into the future will continue to improve. Economists point out that standards of living have increased steadily over time, and living standards for even the poorest nations are "accelerating markedly." [3] GDP per capita and living standards are expected to grow continuously into the foreseeable future, even under the most pessimistic assumptions.[3, p. 170] The OECD, for example, forecasts an average global GDP growth rate of approximately 2% per year for the next several decades.[4, Table A.1]

There is a stark contrast between these two visions of the future because the two groups (scientists and economists) focus on different parts of the economy. Scientists observe the planet's natural capital dwindling, and foresee a quality of life in decline. In contrast, economists observe the stock of manufactured capital growing, and growing increasingly efficient, and foresee quality of life continuing to improve.

The differences between scientists and economists revolve around the understanding and role of capital. Physical scientists often focus on the dependence of our living standards on the available natural capital, but ignore the role of manufactured capital. Economists focus attention on manufactured capital as a primary factor of production (in addition to labor), and ignore the role of natural capital. However, as the oil embargo in the 1970s painfully illustrated, the economy is highly dependent on both types of capital. While it is true that a direct correlation exists between the efficiency of manufactured capital and living standards, natural capital is required to produce, operate, and maintain manufactured capital. Both types of capital are valuable assets that provide the flow of services to the economy needed to produce goods, services, and additional capital for future production.

Natural and manufactured capital are alike in another important way: both depreciate over time as they are used. Manufactured capital "wears out," thereby reducing production capacity. And, we "use up" natural capital when forests are cut down, fossil fuels are depleted, clean air and water are polluted, and wetlands are degraded. As natural capital dwindles, the future capacity for income generation also dwindles. Such depletion of natural capital is the primary concern of many scientists, and it should be concerning to everyone!

Some accounting for natural capital stocks takes place at the national level. The UN produces international standards for the Systems of National Accounts (SNA), which gather, evaluate, and disseminate data on economic activity at the national level. Natural capital that is both owned (by firms or the government) and is used in production, is accounted by the SNA. However, not all countries base their national accounts on the SNA (the United States, China, and France do not, for example), and not all natural capital is "owned." Clean air and water are not accounted in the SNA, for example. Although there is nothing in the SNA framework that prevents accounting for assets (manufactured and natural capital), the focus of national accounting is squarely on income (GDP), not wealth (manufactured and natural capital).[5, p. 415] Even in the US, manufactured capital (fixed assets) is given very little "shelf space," and natural capital is ignored outright.[1] This predilection results in national accounting, particularly in the US, that collects and analyzes a trove of data to produce a robust *income statement* for the economy (GDP) yet mostly ignores the data needed to produce a similarly rigorous *balance sheet* that tracks the value of a nation's wealth (manufactured and natural capital).

By focusing nearly-exclusively on income, national accounting is blind to an important aspect of modern economies: economies deplete natural capital in the pursuit of income. Without a complete national balance sheet alongside an income statement, policy-makers can unwittingly draw down a nation's wealth (natural capital) to generate today's income (GDP). In so doing, future living standards are put at risk.

In contrast to most countries' national accounting, the UN *Inclusive Wealth Report 2012* [6] accounts for all forms of productive capital (natural, human, and manufactured). These data demonstrate that, in fact, a nation's wealth can decline even as its GDP grows. Indeed, for the years 1990–2008, Saudi Arabia, Russia, Venezuela, South Africa, and Nigeria consumed their wealth (and that of future generations) to support consumption by the current generation. Saudi Arabia's GDP per capita grew at 0.4% per year, while its inclusive wealth declined at a rate of 1.1%

[1] Nations may have been lulled into believing that they do not need to manage their portfolio of capital assets (both manufactured and natural) because, to date, human ingenuity has provided replacements for much of the natural capital that has been consumed.

per year. In the most extreme case, Nigeria's GDP per capita grew at 2.5% per year, while its wealth declined at a rate of 1.8% per year. Not all nations consume their wealth in pursuit of today's income. However, wealth is growing at a slower rate than income in most countries. For example, GDP per capita for the US grew on average 1.8% per year, while the nation's inclusive wealth grew at only 0.7% per year.[6, p. 44]

Given the above, we contend that nations need both income statements and balance sheets to ensure sustainability. Nations must monitor and manage not only the goods and services they produce today, but also their stocks of capital and the state of that capital, their bequest to the future. Many questions, such as those found in Section 1.6, are unanswerable without both.

In the ancient fable, six blind men discern six different parts of an elephant and draw different conclusions about the unseen animal before them. Today, scientists and economists discern two different parts of the economy and draw strikingly different conclusions about the unseen future ahead. We contend that both scientists and economists need to take off their blinders and appreciate that capital in all forms (natural, manufactured, human, social, and financial) is necessary to generate the services an economy requires. These two perspectives must be brought together to understand the potential futures we are facing. These two perspectives must inform the data we collect about our economies.

But, what would we do with integrated and comprehensive environmental-economic data, including natural and manufactured capital, if they were routinely and readily available? The goal of this book is to answer that question. Herein, we develop an accounting framework and analysis approach that could take advantage of such data, and we draw several implications from our framework.

We look forward to the day when such data are readily available!

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Michael Carbajales-Dale
Becky Roselius Haney

"Now! Now!" cried the Queen. "Faster! Faster!" And they went so fast that at last they seemed to skim through the air, hardly touching the ground with their feet, till suddenly, just as Alice was getting quite exhausted, they stopped, and she found herself sitting on the ground, breathless and giddy. The Queen propped her against a tree, and said kindly, "You may rest a little now."

Alice looked round her in great surprise. "Why, I do believe we've been under this tree all the time! Everything's just as it was!"

"Of course it is," said the Queen: "what would you have it?"

"Well, in *our* country," said Alice, still panting a little, "you'd generally get to somewhere else—if you ran very fast for a long time, as we've been doing."

"A slow sort of country!" said the Queen. "Now, here, you see, it takes all the running you can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

—Lewis Carroll. 1897. *Through the Looking-Glass and What Alice Found There*. Henry Altemus Company, Philadelphia, p. 49.

Prologue

> *The economic light is brightest under the lamppost of the market, but neither drunks nor statisticians should confine their search there. In extending the accounts, we must endeavor to find dimly lit information outside our old boundaries of search, particularly when the activities are of great value to the nation.* [1, p. 23]
>
> —William Nordhaus

Accounting for the environment has been going on for at least 40 years. The Brundtland Commission (1983–1987) recognized the need to devise rigorous methods for integrating environmental assets into national balance sheets and income statements. In its final report, entitled *Our Common Future*, the commission called for all nations to include a full (economic) accounting of the use and development of natural resources in national accounts:

> The process of economic development must be more soundly based upon the realities of the stock of capital that sustains it. This is rarely done in either developed or developing countries. For example, income from forestry operations is conventionally measured in terms of the value of timber and other products extracted, minus the costs of extraction. The costs of regenerating the forest are not taken into account, unless money is actually spent on such work. Thus figuring profits from logging rarely takes full account of the losses in future revenue incurred through degradation of the forest. Similar incomplete accounting occurs in the exploitation of other natural resources, especially in the case of resources that are not capitalized in enterprise or national accounts: air, water, and soil. In all countries, rich or poor, economic development must take full account in its measurements of growth of the improvement or deterioration in the stock of natural resources.[2, Chapter 2, Paragraph 36]

In response to the call by the Brundtland Commission, economist Peter Bartelmus led an effort at the UN Statistics Division to develop a set of satellite accounts, called the System for Environmental and Economic Accounting (SEEA), which accompanies the UN System of National Accounts framework.[3] The UN published the first Handbook for the SEEA in 1993 and it is now in its third revision.[4] The Philippines served as a pilot study for the new integrated environmental-economic accounting approach, and the island nation's current concerns about mitigating the impacts of rising sea levels has reinvigorated this aspect of their national accounting.[5, 6] The Netherlands currently leads the way among developed nations with a complete National Accounting Matrix that includes Environmental Accounts.[7] Many European Union member states, as well as Canada and Australia have integrated some environmental acounts with their national accounting.[8]

Shortly after the publication of the UN's SEEA methodology, the US Bureau of Economic Analysis (BEA) began development of its own framework for environmental-economic satellite accounts called the Integrated Environmental-

Economic System of Accounts (IEESA). The motivation, methodology, and first set of data tables were published in April 1994.[9] These accounts provided a range of numbers to bracket the value of the stocks of subsoil mineral assets in the nation's portfolio. The IEESA data and the detailed plans for additional phases of development were comprehensive and methodologically rigorous. This effort on the part of the BEA represented a tremendous leap forward for national accounting in the US.

Unfortunately, progress toward integrated environmental-economic accounting in the US came to a screeching halt immediately after the first IEESA tables were published. The US Congress responded swiftly and negatively. The House Report that accompanied the next appropriations bill explicitly forbade the BEA from spending any additional resources to develop or extend the integrated environmental and economic accounting methodology.

> The conferees understand that there has been considerable debate over the years as to the objectivity, methodology, and applicability of "Integrated Environmental-Economic Accounting" or "Green GDP." The conferees understand that the Department [the BEA] has completed the development of Phase I of this initiative. The conferees believe that an independent review, by an external organization such as the National Academy of Sciences, should be conducted to analyze the proposed objectivity, methodology, and application of environmental accounting. The conferees expect BEA to use $400,000 under this account to fund this independent study, as suggested by the House report. The conferees expect BEA to suspend development of Phase II of this initiative until the review has been completed and the results have been submitted to the Committees on Appropriations of the House and the Senate, as well as the appropriate authorizing committees.[10]

Esteemed economist William Nordhaus chaired the National Academy of Sciences (NAS) review panel that evaluated whether the BEA should extend the national income and product accounts to include "assets and production activities associated with natural resources and the environment." [1, p. 2] In 1999, the panel submitted its comprehensive report to Congress strongly recommending that the BEA be authorized to continue producing the environmental-economic satellite accounts.[1]

The report illuminated the need for the nation to keep "comprehensive economic accounts" that "provide a complete reckoning of economic activity, whether it takes place inside or outside the boundary of the marketplace." [1, p. 29] The panel noted that the data would be used by states, local governments, businesses, and investors alike to make sound economic decisions. The panel asked reasonable questions and showed how a system like the IEESA could provide sensible answers. For example, should the timber from an old growth forest be harvested? Using data that are limited to income-generating transactions only, the answer is "yes," because the harvest adds directly to national income. However, the value of foregone "hunting, fishing, and other forms of nonmarket forest recreation" services over time (likely to exceed the value of the harvested timber) cannot be part of the decision unless a system such as the IEESA is in place.[1, p. 30]

Despite the review panel's ringing endorsement of the BEA's work, Congress continued to expressly forbid the BEA's efforts. Appropriations bills through FY 2002 contained the sentence:

> The Committee continues the prohibition on use of funds under this appropriation, or under the Census Bureau appropriation accounts, to carry out the Integrated Environmental-Economic Accounting or "Green GDP" initiative.

Today, congressional appropriations bills no longer prohibit work on the IEESA, but the BEA is understandably gun-shy after their experience in the 1990s. Unfortunately, the BEA did not receive the necessary political backing despite a Democratic administration and two Democratically-controlled chambers of Congress. Restarting an effort similar to the IEESA will require a specific mandate from both the administration and Congress, a significant political task to be sure.

We think that the benefits of "accounting for the environment" will be worth the political efforts needed to resume the practice. After reading this book, we hope you will agree.

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Chapter 1
Introduction

> *Where there is no reliable accounting and therefore no competent knowledge of the economic and ecological effects of our lives, we cannot live lives that are economically and ecologically responsible. It is futile to plead and protest and lobby in favor of public ecological responsibility while, in virtually every act of our private lives, we endorse and support an economic system that is by intention, and perhaps by necessity, ecologically irresponsible.* [1, p. 26]
>
> —Wendell Berry

This book is primarily about accounting and change. It is borne out of a belief that our economies are in constant flux; changing dynamically in the short-term with human behavior and evolving over longer time frames in response to changes in the technological and environmental landscape. Like all real-world systems, economies are messy and chaotic; they do not march orderly from one state to the next. To fully understand our economies, we must appreciate their dynamic nature.

This is also a book about metaphors and models. We use metaphors to simplify and make sense of the world around us. They influence us as stories we tell ourselves to convey meaning, to teach ourselves about the world. Metaphors also inform the mental and empirical models we construct. And, as we collect data (via accounting methods) to assess the validity of those models, our perception of the world is molded and shaped by our accounting; the very accounting that was initially informed by the stories we told ourselves about reality. Our models tell us what aspects of the world are important to value (in the literal sense of making measurements), and also, by extension, which parts of the world (literally) have no value. This process has a deeper normative consequence: the aspects of the world to which our models ascribe value become *valuable*, and those ascribed no value become *worthless*. We believe that traditional models of the economy are based on metaphors that ascribe insufficient value to important drivers of real economic growth, including the availability of natural capital.

1.1 Limits: Extraction, substitution, and assimilation

As metaphors give rise to models, economic models lead to accounting systems that organize data to affirm or deny model predictions. National accounts, particularly in the US, were established to measure the things that our economic models value most: physical production and consumption. However, national accounting systems easily capture changes in *income* from production and consumption, but do not so easily capture changes to the source of a nation's income: its *wealth*. Part of a nation's wealth is its natural resources. So the focus on income means that we are not accounting for natural assets, not even the important categories of materials and energy,[1] in a way that can inform meaningful economic discussion or lead to enlightened natural resource and energy policies. Whether you think this is a problem depends, in part, on: whether you think the world's economies are approaching natural resource extraction limits; whether you think the materials and energy upon which our economies currently depend can be easily substituted by other, readily-available, inexpensive resources; and whether you think that the world's economies have exceeded the biosphere's waste assimilation capacity.

1.1.1 Natural resource extraction limits

For many commodities, supply is becoming scarce relative to demand, with oil providing, arguably, the most important example. Both economic and physical arguments can be used to show that the world is facing natural resource extraction limits.

Economic theory predicts that as demand for a product increases, the increased profitability of rising prices will induce current producers to increase supply, entice new producers to enter the market, and encourage other producers to offer close substitutes. In the case of natural resources, if that does not occur there is evidence that resource extraction limits are being reached. This is happening today in the oil market. For much of the twentieth century, the price of oil remained below \$20 per barrel. However, in the 2001–2008 timeframe, the inflation-adjusted price of oil increased 260%, from around \$35 to a peak of \$126 per barrel (in constant 2010 USD). During the same period, world oil production rose from 78 million barrels per day to 86 million barrels per day, an increase of only 10%.[2] Since 2010, the price of oil has remained over \$80 per barrel, suggesting that production cannot increase quickly enough to bring prices back down to historical levels. Persistently high prices for such an important commodity suggest very real limits to production; that supply is constrained relative to demand. We are reaching natural resource extraction limits.

On a physical basis, it is evident that easier-to-reach resources are extracted first. After the easier-to-reach resources are depleted (such as oil in West Texas), more difficult-to-extract resources must be pursued, further offshore, in harsher environments, and with enhanced techniques (such as steam flooding or hydraulic fracturing). Sometimes, new, energy-intensive techniques are required for difficult deposits, such as oil sands. Turning to materials extraction, the production of finer-grade ores requires the processing of greater amounts of raw material, resulting in increasing mining tailings.[2] The processing of extra raw material takes more energy, and the energetic cost of extracting many materials is certainly increasing.[4–6] This

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[1] Note that income is counted as a monetary rate (e.g. \$/year), not a physical rate (e.g. kg of material per year) or an energy rate (e.g. kJ of energy per year).

[2] Mining tailings are the unwanted materials that remain after mining processes have removed economically valuable materials.[3]

process has been labeled the "Red Queen" effect, where we must extract increasingly more resources to achieve the same level of production—run faster and faster just to stay in the same place.[7–10] The facts that (a) producers continue to reach deeper and farther and (b) energetic costs of production continue to rise are further evidence that the world is reaching natural resource extraction limits.

1.1.2 Substitutability of natural resources

The ability to substitute human-made capital for natural resources or one natural resource for another may alleviate the problem of natural resource scarcity relative to demand, at least temporarily. There are many historical examples of this sort of substitution occurring, particularly in the energy sector. Deforestation within Europe, primarily for fuel to smelt iron, [11] prompted the switch from wood to coal. Whale oil was replaced by petroleum-based kerosene for lighting and coal has also been replaced by oil for other uses, especially transportation.[12] More recently, natural gas has begun to replace oil in many applications. Therefore, goes the argument, substitution may continually stave off resource scarcity. But, there is evidence both at the macroeconomic level and at a technical level that there are limits to energy substitution.

Pelli, in a study of 21 countries found that clean[3] and dirty[4] inputs to electricity production are complementary (as opposed to substitutable).[13] His conclusion is dire:

> On the one hand, according to the model, if we keep producing electricity using dirty inputs, we head toward an environmental disaster. On the other hand, looking at the empirical results, it seems impossible to stop producing electricity with polluting resources. The policy implication of this paper thus, seems to be that we need more important subsidies to research, as fast as possible, and high carbon taxes combined with a complete halt of the growth rate of the production of electricity. In this way, according to the model, we may be able to avoid an environmental disaster.[13, p. 25]

In a meta-analysis of 15 papers that studied the economic evidence for macro-substitutability among factors of production (materials, capital, labor, and energy), de Wit et. al. [14] found that the elasticity of substitution was below unity for all combinations of factors of production. Furthermore, they argue that,

> [because all of the] results show elasticity of substitution below unity, none of the factor inputs are perfectly substitutable and all tend toward complementarity in varying degrees. Such results suggest that transitions from one production or consumption structure to another can be disruptive and that the transitions need to be modeled dynamically to the extent possible.[14, p. 8]

There are limits to substitution from a technical point of view, as well. For example, there are no known substitutes for oil in many sectors of the economy.[15]

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[3] Nuclear, conventional hydroelectric power, wood and waste biomass, geothermal, solar/photovoltaic, and wind

[4] Coal, petroleum, natural gas, and other gasses

Biofuels were hailed by many as a viable alternative to fossil fuels, but there is not enough land for biofuels to meet current liquid fuel demand without displacing food production. These realities highlight the fact that within tightly coupled, complex systems (such as the energy–food system), changes in one part of the system often have unintended consequences elsewhere. For example, the US obtains 13 billion gallons of bio-ethanol (less than 10% of the 134 billion gallons of domestic fuel consumption in 2012) by diverting approximately 40% of domestic corn production for biofuel.[2, 16] This policy has had dramatic impacts on global food security, with each billion gallon increase of biofuel production believed to cause a 2–3% increase in corn prices.[17]

Often, the substitution of manufactured resources for natural resources requires the use of greater amounts of energy. For example, the production of fresh water from recycled or seawater can be particularly energy intensive. Thus, the substitution of a manufactured resource (desalinated water) for a natural resource (fresh water) requires greater inputs of natural resources (in this case, free energy) to achieve. Whereas material resources can, at least in theory, be recycled indefinitely, free energy is the ultimate limiting resource, because energy cannot be 100% recycled.

For many commodities today, limited or negligible substitution is possible, and the complex, highly-coupled nature of modern economies often leads to unintended consequences (usually involving increased energy consumption) when substitution is technically possible. We are reaching limits of substitutability for many important materials and energy sources for our economies.[5]

1.1.3 Overloading the biosphere's assimilative capacity

There are many examples of society locally exceeding the assimilation capacity of the biosphere. In 1952, London city experienced a lethal smog cloud, due to coal-burning power stations, that, according to some, claimed as many as 12,000 lives.[18, 19] Many Chinese cities are currently experiencing similar problems. Such point-source, localized environmental problems can often be overcome by regulations. In Britain, two Clean Air Acts regulated emissions from both industrial and domestic sources.[20] In the US, emissions regulations in California have significantly reduced Los Angeles' legendary smog problem.

However, there is mounting evidence that systemic ecosystem damage occurs due to the externalized costs of growing economies. Of course, the perspective of *external* and *internal* is subjective. A cost externalized by one agent must be internalized by another.[21, 22] So, natural systems often bear the burden of human production. So-called "free" natural resources are exploited, land-use is altered to better suit society's needs, and other species are marginalized by the encroachment of human activity.[23] In many cases, as more waste is deposited into ecosystems, and as the structures of ecosystems are permanently altered for human desires, the assimilation

[5] The issues of resource scarcity and substitution will be revisited in the Materials chapter (2) and the Energy chapter (3).

capacity of the biosphere declines. When the assimilation capacity of the biosphere is exceeded, services provided by the biosphere may be disrupted.[24]

Many wastes are either emitted from multiple locations or have significant non-local effects. Examples include: algal blooms and so-called "dead zones" due to over-use of agricultural fertilizers; over-use of agricultural pesticides; build-up of persistent organic pollutants, especially endocrine disruptors, such as PCBs and BPAs;[6] bio-accumulation of heavy metals released due to mineral extraction and industrial processing; ozone depletion due to release of chlorinated gases (primarily halocarbons); acid rain due to release of sulfur dioxides; release of radioactive materials; detergents in sewage; invasive species; oil spills; and, of course, greenhouse gas emissions.[24–26] In each case, human economic activity has increased the concentration of wastes to the point where the biosphere can no longer maintain previous levels of ecosystem service. We are reaching assimilation limits.

1.2 Material and energy transformation

Because the world is facing natural resource extraction limits (especially for some forms of energy) and because we are exceeding the assimilative capacity of the biosphere, it follows that a structural transformation of the economy is imminent. Society cannot accelerate rates of material extraction and waste production indefinitely.

Because substitutability is finite, it follows that reaching the extraction and assimilation limits of the biosphere will bring significant societal challenges. The question is: how will this transformation unfold? How will our economies cope with the challenges?

We contend that materials and energy transformations will either *happen to* us, or we will *plan for* them. At present, transitions are happening *to* us: very little materials or energy planning occurs at the industry-wide or government level.[7] Because it is likely that unplanned transformations will be rocky and difficult, we believe that some type of planning is needed.

Clearly, the first step for effective planning is knowledge of the current state of affairs. We need to know the existing materials and energy structure of our economies. This implies that we should know the rates at which the world's economies consume raw materials and emit wastes back to the biosphere. We need to understand the connections between the biosphere and the economies of the world. But, we also need to know how materials and energy consumption are likely to evolve in the future. We should know where and at what rate materials and embodied energy accumulate in economic infrastructure. We should know the material and energy costs

[6] Polychlorinated biphenyl (PCB) is a synthetic organic chemical often used as a dielectric or coolant in electrical equipment. It is a known carcinogen. Bisphenol (BP) A is a carbon-based synthetic compound used in the production of plastics and epoxy resins. It exhibits hormone-like properties at high doses.

[7] On the world stage, notable exceptions include the UN Environment Programme's International Resource Panel [27] and the United Nations System of Environmental-Economic Accounting.[28]

of maintaining the increasingly-complex infrastructure of society. We should have a sense of the transient and variable nature of economies and the materials and energy flows that sustain them. In short, we need to be *accounting for the environment*![8] Despite this need, we (i.e., society at large) are not accounting in a way that helps us plan for the economic challenges that will accompany the impending materials and energy transformation. All of which leads to a burning question, one with significant consequences for the future:

> How can you maintain a system of national accounts without accounting for natural assets?

With that in mind, the purpose of this book is to develop a dynamic model to help us "account for the environment" with the objective of planning for impending materials and energy transformations.

1.3 Metaphors and models

Before moving ahead with the work of developing our dynamic model, it is useful to consider how society has come to this point. How is it that we don't account for the environment when considering materials and energy flows into, within, and out of the economy? The classical economists certainly appreciated the dependence of economic activity on bio-physical processes.[29, 6, 30] However, somewhere between William Stanley Jevons' 1865 assessment that "the very existence of Britain, as a great nation" [31, IV.3] was tied to a continued supply of low-cost coal and Julian Simon's 1998 statement that "natural resources are not finite in any economic sense," [32, p. 54] the importance of the biosphere was lost.

1.3.1 The clockwork metaphor

Indeed, most economics textbooks today depict the economy as in Figure 1.1. Goods and services flow from the production sector to the household sector (consumption) in exchange for payments. The factors of production (labor and capital) flow from the household sector to the production sector in exchange for wages and rents. Attention is primarily focused on the circular flow of money (dashed line).

This traditional model of the economy (Figure 1.1) is unashamedly mechanistic. General equilibrium models of the economy [33, 34] were borrowed directly from

[8] The title of this book is a *triple entendre*. First, we should take the environment "into *account*" when developing our system of national accounts. As discussed in the Preface, at present, we are not. Second, we should be maintaining and disseminating records or accounts of environmental assets. In this usage, *account* is a noun referring to our endowment of natural resources. Third, we should develop our system of national accounts *for the benefit of* the environment, with the understanding that a healthy environment sustains a healthy economy. In this sense, *accounting* is used as a verb with a telos.

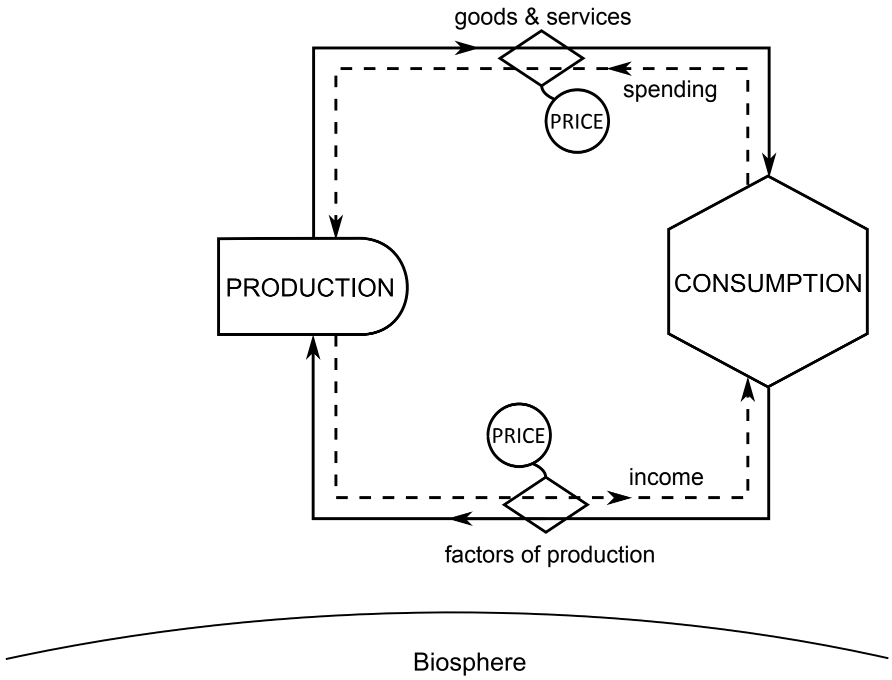

Fig. 1.1 In the traditional model, the economy is represented as a circular flow of goods and services between two sectors. The producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers.

classical physics' models of mechanical equilibrium which, in turn, arose from the "clockwork universe" metaphor.[35] As discussed above, the clockwork metaphor is an example of a simplification that helps us make sense of the world around us. Metaphors inform our thinking about the real world, but consequently, they also constrain our ability to frame reality. We 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.[9] Classical physics told us the universe is *like* clockwork, so we began to interact with the universe as if it *really were* clockwork. It then became easy to collect data that confirmed the clockwork model, because the model told us which data to collect.

The clockwork metaphor and the traditional model of the economy preclude any sort of connection between the economy and the biosphere. Thus, only the internal dynamics of the economy are important. They tell us that natural resources are unimportant, effectively assuming that the biosphere will always provide. If a particular resource becomes scarce, substitution to a different, more-readily-available resource will be made. They tell us that wastes are quantitatively unimportant,

[9] This fallacious process is called *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*.[36]

effectively assuming that the biosphere has infinite assimilative capacity. Finally, the clockwork metaphor and traditional model of the economy tell us that economic forces (through prices and the market mechanism) are sufficient to efficiently guide any necessary transition within the economy. Any physical constraints that the biosphere places on the allocation of resources, distribution of outputs, and scale of an economy are outside the scope of neoclassical economic discussion.[37] In short, the clockwork metaphor and the traditional model of the economy tell us that the clockwork-economy can and will carry on.

Because Figure 1.1 has no flow of energy into the economy, we may consider it 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.[38] However, thermodynamics tells us that all physical processes require a transfer of energy.

1.3.2 The machine metaphor

The limits of the clockwork metaphor and traditional model of the economy were exposed by the oil shocks of the 1970s. Suddenly the global economy "stalled" due to lack of a single, highly-constrained resource: fuel. Many came to realize that energy input is required for successful operation of an economic "engine." Thus, a machine metaphor and accompanying engine model for the economy rose to prominence in the late 1970s and early 1980s. The need to include energy resources in the economic picture spurred the efforts of early (net) energy analysts.[39, 40]

The engine model accounts for energy flows from the biosphere to the economy and is shown in Figure 1.2. With the new metaphor, the economy changed from an *isolated* system (Figure 1.1) to a *closed* system (Figure 1.2). The importance of input energy is acknowledged, but wastes are absent. And, the biosphere is relegated to the position of provider of energy resources; the gas station of the economy.[41]

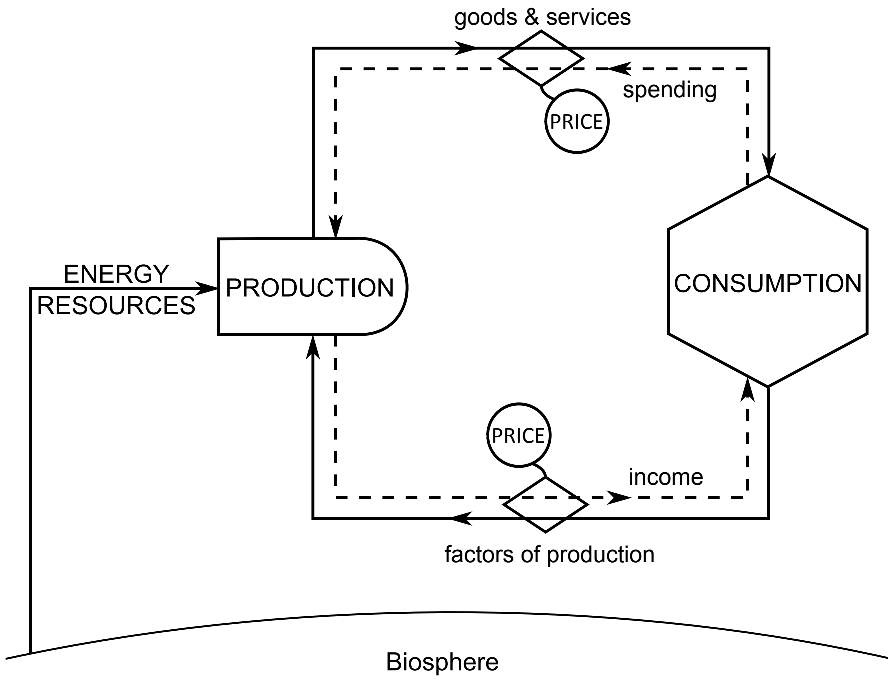

Fig. 1.2 The machine model of the economy includes flows of energy into the economy from the biosphere. This may be considered a perpetual motion machine of the second kind.

The machine metaphor and engine model are still very much mechanistic. Much like the engines of the Industrial Revolution, the economic engine is assumed to be well-behaved and amenable to control. Even today, machine metaphors abound in our economic discussions. We speak of "fueling" the "economic engine" lest it should "stall." [42] Like a well-running engine, the economy is assumed to be resilient to small or even quite large perturbations. It can either self-correct, or be corrected with adjustments to a few predictable policy levers.

But, in light of the challenges discussed above, how accurate is the engine model?

According to the Second Law of Thermodynamics, all real-world processes involve the degradation of material and especially energy resources and the creation of entropy. High quality (low entropy) material and energy come in; low quality (high entropy) material and energy go out. The depiction in Figure 1.2 can be classified as a perpetual motion machine of the *second kind*: it perfectly converts energy resources into work (useful services) without generating any entropy, in violation of the Second Law of Thermodynamics. Because the generation of high entropy (low quality) output is a *necessary* feature of *all* processes (including economic processes) then the generation of wastes is a *normal* feature of economic processes, not an anomaly. Within a closed system, such as the earth, these wastes soon accumulate, necessitating the change to a "spaceship" economy, wherein account is made of the waste outflows from the economy.

We need a different model.

1.3.3 A new metaphor

When our collective imagination is stuck on a metaphor that informs models in which the economy is isolated from or closed to the biosphere, the suggestion to "account for the environment" is unconvincing, and the challenges cited earlier (natural resource extraction limits, difficulty of material and energy substitutions, and exceeding the biosphere's waste assimilation capacity) seem unimportant.

Mounting evidence shows otherwise.

Thus, we need to find a new way to understand the complex, messy dynamics of real-world economies; we need a new way to make sense of real-world events; we need a new way to learn where and how economies can go wrong; and we need to plan for the impending materials and energy transformations. To do so, we had better be counting data to assess *dynamic* models guided by metaphors that tell us *more* than "the world is an orderly place." Our counting needs to be informed by metaphors and models that are able to cope with rapid transience and transformation, not just ordered stability.

We need a new metaphor.

1.4 An apt metaphor for the economy

If the clockwork and machine metaphors are unsuitable, what might an apt metaphor for the economy be? And, if we find an apt metaphor, what types of models would it inform? Furthermore, what data would the models tell us to collect? That is, how should we go about accounting for the environment?

To begin the search for an apt metaphor, we might first ask the question, what characteristics should the metaphor possess? In our opinion, an apt metaphor should account for the facts that a real economy:

1. intakes material and energy from the biosphere
2. exchanges materials, energy, and information internally
3. discharges material and energy wastes to the biosphere
4. is affected by energetic costs
5. is 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. embodies energy in material stocks, and
8. maintains organizational structure despite changes in the environment.[10]

[10] We note that several areas of the literature speak to the items in this list. Material Flow Analysis (MFA) and Economy-Wide Material Flow Analys (EW-MFA) stress the importance of material

Living metabolisms[11] 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 1.1 and 1.2 to include the facts in items (1)–(3), we obtain Figure 1.3. 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 into 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.[43–45]

1.5 An apt material, energy, and economy model

As discussed in Section 1.3, metaphors give rise to models. So, a natural question is: "what types of models does the metabolism metaphor inform?"

In our opinion, apt models should have the following characteristics:

1. account for flows of materials and energy into, within, and out of the economy,
2. account for accumulation of materials and energy within the economy,
3. provide metrics that relate energy demands and economic value, and
4. provide results that are comparable against existing (or expanded) national accounting.

Material and energy flow balance equations, often employed by thermodynamicists, can account for both flows (1) and accumulation (2) of materials and energy within systems. We will adapt an existing Input-Output (I-O) energy analysis method to develop a technique for obtaining metrics of energy and economic value (3).[12] Finally, we note that systems of national accounts use the economic sector as their level of analysis. Thus, our models should be also implemented at the economic

intake by the economy. (See Section 2.5.) The Input-Output (I-O) method highlights the effects of internal exchanges of material and information with economies. (See Chapter 6.) Life-Cycle Assessment (LCA) techniques focus attention on otherwise-neglected wastes. (See Section 6.6.) Net Energy Analysis (NEA) predicts that energy resource scarcity reduces Energy Return on Investment (EROI) and increases energy prices. (See Sections 3.3 and 8.4.) The Energy Input-Output (EI-O) method gives prominence to energetic costs for internal material and energy flows. (See Chapter 6.) And, thermodynamic control-volume modeling describes transient behavior and system transformations. (See Chapters 2–5.)

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

[12] See Chapter 6 for details of the I-O method.

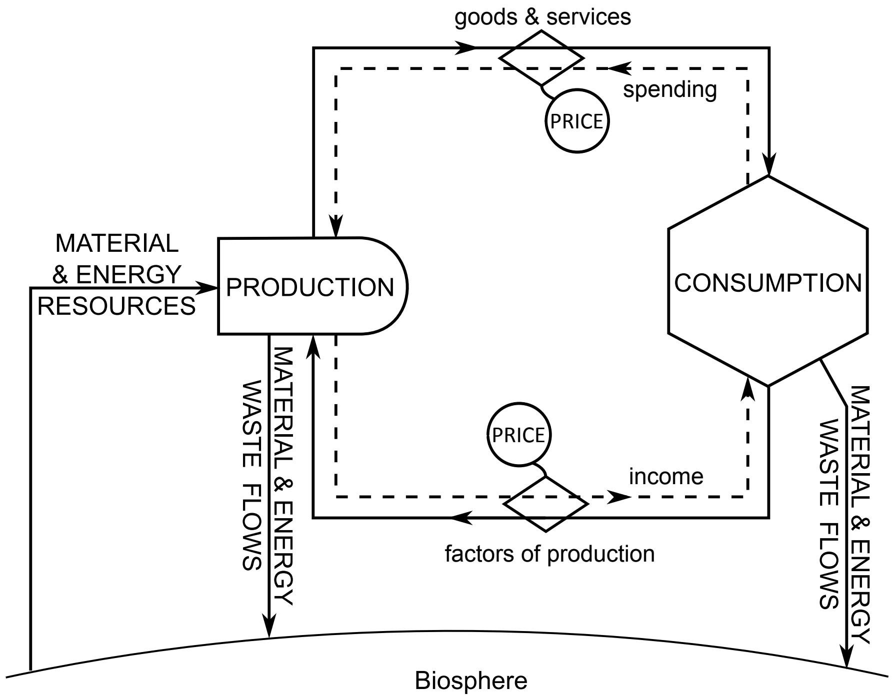

Fig. 1.3 The metabolism model provides a comprehensive view of the economy, fully consistent with the laws of thermodynamics, including degraded resources (waste) expelled to the environment as a necessary consequence of economic activity.

sector level so that results from the models we develop can be compared against existing (or expanded) national accounting (4).

1.6 What to count?

We contend that society is not accounting materials and energy adequately to prepare for the coming material and energy transformations. After settling on a new metaphor for the economy, and after deciding to employ transient thermodynamic equations to develop our model, are we any further ahead? We think so. We believe the key to understanding how energy transformations will unfold involves specifically understanding how

- materials,
- energy,
- embodied energy, and
- economic value

each flow and accumulate within society's metabolism, the economy. Of course, each of the above items interacts with the others and the biosphere dynamically. If we can begin to carefully track these items, we will be on our way to gathering the information required to assist planning for upcoming materials and energy transformations.

A model informed by the metabolism metaphor may allow consumers, producers, and policy-makers to answer critical questions that are not answerable today. Example questions include:

1. 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?
2. How is fossil fuel dependency embedded in the interlocking fabric of the economy?
3. How will economies that are dependent on coal, oil, and other forms of non-renewable energy transition to renewable forms of energy?
4. How might an economy be affected as an increasing share of production is directed toward replacing degraded ecosystem services? [46, p. 221]

To summarize Sections 1.4–1.6, our approach 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.

If successful, we will have developed an analysis framework that allows us to *account for the environment*.

1.7 Structure of the book

The bulleted list in Section 1.6 provides the beginning of the structure for the rest of this book.

Part I addresses flows of physical matter and energy through the economy. Chapter 2 discusses material flows and accumulation. Flows of energy are covered in Chapter 3, and a rigorous, thermodynamics-based definition of and accounting for embodied energy is presented in Chapter 4.

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 5. In Chapter 6, we combine the results from Chapters 4 and 5 to calculate 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 7 draws out some of the direct implications of our framework. Chapter 8 looks at

Table 1.1 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

unfinished business: practical, conceptual, and theoretical issues that arise in the development of this framework. And, we end with a summary in Chapter 9.

Throughout the methodological chapters (2–6), our accounting framework is developed through a series of increasingly-disaggregated models of the economy (Table 1.1), and we use the US auto industry as a running example for application and discussion.

**** The next two paragraphs are duplicated from Section 2.5 (Materials in the US Auto Industry). We duplicated them here temporarily so that the editors can see the purpose of and justification for the auto industry example. ****

The running example of the US auto industry demonstrates that our dynamic model can be tied into national accounts. The US auto industry example shows where data are available (e.g., economic value, Chapter 5), where it is old (e.g., energy intensity, Chapter 6), and where it has never been available (e.g., accumulated embodied energy, Chapter 4). The US auto industry is, therefore, illustrative of the challenges inherent in obtaining data that would feed the model.

The auto industry has been used previously in the literature in both process-based [47–53] and Input-Output [54–56] analysis methods, Furthermore, the industry remains a large portion of many industrialized economies, is very resource intensive, has obvious links with energy because its health is sensitive to disruptions in energy supplies, and the industry also shows evidence of post-industrial decline (shrinking profit margins, etc.).

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